EVALUATING ALTERNATIVES FOR DRINKING WATER AT DEPLOYED LOCATIONS

THESIS

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Abstract

Because of potential improvements to water security and cost savings, military decision makers may want to consider new means of providing potable water to Airmen in deployed locations. Drilling for water and field bottling show great potential because of the increased security and lower per unit cost when compared to bottled water from approved sources. However, the selection of the best means to supply water is a hard decision which must balance multiple objectives (e.g., security, palatability, and convenience) against limited resources (e.g., cost, airlift, trucks, and personnel).

The Value Focused Thinking (VFT) methodology was used to create a multi-objective decision analysis model that quantifies a decision-maker's values regarding the many different means of providing potable water. Consisting of four fundamental values and seventeen measures, the model captures the Air Force's objectives, through a proxy decision-maker, regarding this decision. Using three different notional bases, the model was tested by evaluating five initial alternatives for each base. Sensitivity analysis was also conducted to provide additional insight into the tradeoffs and to generate potentially even better alternatives which were tailored to the specific location and decision-maker's objectives. Although results will certainly vary based on individual situations (e.g. temporary bases), the model shows that more of the decision-maker's values are met if water is supplied through the drilling of wells versus the continued reliance on commercial bottled water. More emphasis on drilling wells would not only potentially save hundreds of millions of dollars but would also provide a much safer water supply, thereby improving the chances for operational success. Finally, in consideration of the typical Airman's acceptance of drinking water, well water used in conjunction with the Army's field bottler may be just what the Air Force needs now.

This is dedicated to Airmen serving in Southwest Asia. Their perseverance and professionalism despite brutal heat, choking dust, and the many difficulties of being separated from family has inspired me and motivated me though this research effort.

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Brian S. Hughes

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Chapter 1. Introduction

Water sabotage by enemies is not a new concern. During the siege of Cirrha around 590 B.C., Solon of Athens is said to have used hellebore roots (a purgative) to poison the water in an aqueduct leading from the Pleistrus River (Sidel, 1997). As far back as 300 B.C., the Romans buried some of their aqueducts 50 feet underground out of concern an enemy might neutralize their supply (Hershel, 1973). While these examples represent ancient history, similar incidents have been reported throughout history, including recent history.

1.1 General Background

As the following examples illustrate, the sabotage of potable water supplies is a concern for civil defense authorities as well as the military. From the civil perspective, Italian police reported in December 2003 that a saboteur, referred to in the press as the "Aquabomber," was contaminating bottled water with small amounts of poisonous liquids (Reuters, 2003). In another example, insurgents destroyed water mains in Baghdad in July 2005, thereby affecting an estimated one million people (UN, 2005). From the military side, cyanide was detected in a tank of water being delivered by a contractor to an airbase in Kuwait in February 2003 (CENTAFBEE, 2003). Although the water was refused and the truck was rejected, it was never determined whether the contamination was intentional or residue accidentally leftover from industrial use.

While "hydrate or die" may be a hyperbolic commercial slogan, it is not an untrue one (Karp, 2005). This is particularly true for military operations, where it is imperative that safe, reliable, drinking water be available in sufficient quantities. At least five liters per day per person of water is generally considered a healthy water intake (DAF, 2003). In hot climates, it can be as much as 15 liters per day (AFMAN(I) 48-138, 2003). When this is multiplied by the thousands of troops that may be in any given location, the total water requirements can be enormous. Additionally, the logistics of getting potable water safely to the battlefield may be a challenge. For example, to prepare for its 1950 invasion at Inchon, Korea, the United States (U.S.) scrubbed Japanese oil tankers and decontaminated them of oil so they could be used to carry millions of gallons of potable water. Despite these cleansing efforts, oil contaminated the water; medics subsequently reported the chief cause of illness during the invasion was gastroenteritis associated with oil-contaminated drinking water (Cowdrey, 1987).

Israel provides a more successful case of going to great lengths to ensure sufficient water for its troops during the 1967-1973 Egyptian-Israeli wars. As part of its water doctrine, Israel ran pipelines with cooling systems at dispensing facilities and required officers to enforce regular hydration. Officers that failed to enforce the prescribed hydration regimen were subject to court-martial and a mandatory 35-day jail sentence. Israel's doctrine proved very successful: During the 6 days of combat, Israel suffered few heatstroke casualties compared to 20,000 for Egypt (Wyatt, 2002).

Whether by tanker ship, pipeline, or convoys, logistics are a major concern. Compounding the logistical challenge is the threat posed by enemy forces. However, the

threat paradigm facing U.S. military forces has changed dramatically in recent years. This is best described by Steele (2002).

> The **old threat paradigm** emphasized strategic nuclear and conventional forces associated with a government, with static orders of battle, linear in development and deployment over time. They were employed in accordance with well-understood rules of engagement and doctrine, were relatively easy to detect in mobilization and were supported by generally recognizable intelligence assets. The **new threat paradigm**, in contrast, is generally nongovernmental (or a failed state), nonconventional, dynamic or random and nonlinear in its emergence, with no constraints or rules of engagement. It has no known doctrine, is almost impossible to predict in advance and is supported by an unlimited 5th column of criminals, terrorists, drug traffickers, drug addicts and corrupt individuals. It is, in a word, asymmetric.

Under this new threat paradigm, "Future adversaries seeking asymmetric advantage will necessarily identify and attempt to exploit vulnerable U.S. Air Force (USAF) centers of gravity (COG)" (Hicks, 1999). Potable water is one such COG and the dependence of our enemies on asymmetrical tactics suggests a closer look at the way the U.S. Air Force supplies and protects potable water in deployed locations is warranted.

Before 1990, most of the Air Force's deployed units used Reverse Osmosis Water Purification Units (ROWPU) for drinking water (Wood, 2003). A ROWPU is a tactical water filtration system that uses reverse osmosis and is capable of removing dissolved solids, salts, molecules, and compounds with size greater than 0.001 micrometers (Osmonics, 1997). The cost of purifying water with ROWPUs in deployed settings is approximately 0.8 to 1.6 cents per liter (Wyatt, 2002). However, this reliance on ROWPUs has changed over the past 15 years. Since 1990, bottled water is used almost exclusively even though its cost is approximately 52 cents per liter (Wyatt, 2002), which is about 50 times more expensive than using ROWPU. Bottled water is typically procured from plants in the local or regional economy that are certified by the U.S. Army.

However, regional procurement generates significant logistical and force protection issues. Even if one assumes the enemy will not target bottled water, it is often less safe and less clean than tap water obtained in the United States, despite public perceptions to the contrary (BWL, 2005). Some have even called bottled water the "Nectar of the Frauds" (Aslam, 2006).

Arguably, the best quality water in field operations comes from ROWPU, but it is not invulnerable to failures or attacks. For example, ROWPU depends on the availability of electrical power, a source of raw water, and a means to store and distribute the product water. Also, the technological basis for ROWPU (e.g., reverse osmosis with carbon adsorption, and chlorine disinfection) is well known. Therefore, it seems entirely possible that an intelligent, well-trained enemy with unlimited resources could defeat a ROWPU-based system if given the opportunity to do so. On the other hand, the case of the "Aquabomber" and images of burning trucks (Richards et al., 2005) demonstrate sufficiently the vulnerabilities associated with bottled water.

The two predominant alternatives for providing water in field operations are bottled water and ROWPU's. However, if the Air Force builds a semi-permanent facility, such as an expeditionary airbase, that already includes heavy construction costs, it might make sense to invest in a more permanent, conventional potable water infrastructure. This would achieve greater security as well as lowering long-term operating costs. This scenario also makes sense if the plan is to eventually turn the facility over to the local government.

There is also a growing trend to use contractors, even in forward areas, to provide for food service, construction, transportation, and other support services. It might be

cost-effective to also use contractors to build and operate water treatment, storage, and distribution facilities. Likewise, there is a trend to deploy as part of an international coalition. Therefore, it maybe effective to use coalition forces to build and operate these facilities.

For alternative methods, ROWPUs and bottled water can be enhanced, combined, or replaced by either conventional or advanced treatment processes; these processes may be specific to military use or based on commercially available technologies. Some of the treatments that might be considered for delivering safe water include conventional (e.g., flocculation, sedimentation, sand filtration, chlorination) or advanced (e.g., various types of membrane filtration or distillation) processes. Another factor when considering alternative methods is whether the system will be installed on a permanent or semi-permanent basis.

1.2 Problem Statement

Because of the increased vulnerabilities to water supplies and the high cost of bottled water, perhaps it makes sense to raise the question: What is the best way to provide potable water to the Air Force's deployed units? Given the considerations mentioned in the previous section and allowing for the possibility of additional considerations, this is not only a difficult decision but a subjective one as well. Although the best alternatives will balance security, cost, and logistical concerns, they are very dependent on geographical variables and the expeditionary base commander's objectives. Therefore, a means of evaluating potable water alternatives would be very useful.

1.3 Research Objective and Investigative Questions

The objective of this research is to develop a multi-objective decision analysis model for the evaluation and selection of potable water supply alternatives at deployed locations. The model will be used to delineate a decision maker's (e.g., a commander's) multiple objectives and develop a list of alternatives that best meets those objectives. To meet the goal of this research, the following investigative questions will be addressed.

1. What are the characteristics, advantages, and disadvantages of different methods of providing potable water in a deployed location?
2. What is important to Air Force decision-makers when selecting a potable water supply method?
3. Which types of potable water supply methods appear to more suitable for different deployed regions?
4. How do changes in decision makers' values influence the outcome of the decision model?

1.4 Methodology

Value Focused Thinking (VFT), a subset of decision analysis, is becoming more prevalent as a tool to gain insight into complicated choices (Jurk, 2002). VFT is increasingly used in the Air Force, perhaps because it flows naturally from the paradigm of commanders choosing the objectives and subordinates recommending solutions that meet those objectives. The VFT methodology provides a number of particular advantages. It provides a way for multiple stakeholders to contribute productively towards the development of solutions. It also balances multiple objectives and shows the decision-maker how well each proposed alternative meets those objectives. By focusing on values, it facilitates the search for better alternatives. Finally, it provides an objective, repeatable, and defendable rational for making a decision (Keeney, 1996).

To execute the methodology, a series of meetings will be held with the proxy decision-makers and stakeholders to identify, define and organize the considerations associated with providing field water in such a way that they can be mathematically modeled. Three scenarios, with typical technical and force protection challenges, will be used to tailor the model to suit notional commanders' objectives for those particular scenarios. A handful of alternatives will be scored for each scenario and sensitivity analyses will be performed. The product of this research should be a model which efficiently evaluates alternatives in a way that is "objective, defendable, and repeatable" (Kirkwood, 1997). Additionally, the model should provide insight which may lead to the consideration of even better alternatives (Weir, 2005).

1.5 Scope and limitations

This research will be limited in scope, applicability, and rigor. Although the need for water security is similar for continental United States (CONUS) and field operations, this research will be particularly focused on field operations. The type of model proposed depends upon subjective weightings from decision-makers with a particular scenario in mind, thus the results are valid only for those particular decision-makers and do not apply universally to other field operations. In other words, the analysis would be different for each decision-maker. Costs during field operations can vary widely depending on the local availability and the nature of the engagement. Although the purpose of this research is not to develop a cost model for field operations, every attempt will be made to use realistic cost estimates; however, it is likely that real world costs may be significantly different.

1.6 Thesis Outline

Chapter 2 provides a review of the literature related to this research. It includes a discussion of the challenges inherent in providing potable water at deployed locations. It also covers some of the recent advances in water treatment, packaging, and well drilling. Finally, it includes a look at decision analysis theory and the particular methodology chosen for this research. Chapter 3 documents the development of the model, while Chapter 4 explores the implementation of the model using three realistic locations/scenarios. The analysis will rely on notional data since real data is not necessary to meet the objectives of this research. Chapter 5 summarizes the conclusions and insights gained from this thesis effort. It also reviews the strengths and weaknesses of the model and provides suggestions for future research on this topic.

Chapter 2. Literature Review

The purpose of this chapter is to provide enough technical background to understand the problem and then to introduce the methodology which will be used in this research effort. First, it will expand upon the threat background provided in Chapter 1 and analyze intentional and unintentional threats to water supplies. Second, it will summarize the elements of water security (e.g., policy and physical systems). Third, it will summarize the requirements, advantages, and disadvantages of both conventional and advanced water treatment technologies. Finally, it will introduce the reader to decision analysis and the value focused thinking (VFT) methodology used in this research.

2.1 Threats to Water Supplies

To begin to understand the threats to water supplies, it is necessary to understand the prevalence of water-borne illnesses inside and especially outside the United States. Although safe drinking water is often taken for granted in the United States, outbreaks of waterborne disease do occur (Lee, 2002); however, these incidents are relatively few compared with much of the world where unsafe drinking water and inadequate sanitation cause an estimated 5 million deaths and 200 million cases of diarrhea each year (Hunter, 2000).

Threats to water supplies often concern *contamination* of the water supply with chemicals, microbiological agents, or radionuclides. These can enter the water system locally or from many miles away and are often the result of human and/or animal

activities (EPA, 2003). To be specific, contaminants can enter the water at the source, anywhere along the distribution system, or at the point of use. Foran and Brosnan (2000) describe these threats as follows:

> Threats to drinking water supplies have plagued humans since the dawn of history. These threats range from the spectacular and highly disruptive (e.g., floods, spills of oil or toxic chemicals) to the more mundane, but not necessarily less important, such as impacts from storm pipe discharges or runoff from agricultural lands.

The events that cause the contamination can range from dramatic to subtle. Whether unintentional or deliberate, these threats can have potentially life-threatening, incapacitating, or chronic effects on human health. To gain a better perspective, both unintentional and deliberate threats are examined in subsequent paragraphs.

2.1.1 Unintentional Contamination

The most dramatic unintentional threat to water supplies is natural disasters, which often cause water mains to break, sewage systems to backup and equipment outages due to no electricity. In these instances, it is common for public health authorities to issue a "boil order." As the Center for Disease Control (CDC) stated, "Water may not be safe to drink, clean with, or bathe in after an emergency such as a hurricane or flood" (CDC, 2005).

Hurricane Katrina provides a recent example. Three days after Katrina struck, President Bush listed the importance of providing safe water to the area as second only to saving lives. At that time, the Department of Transportation had already shipped 13.4 million liters of water in support of relief efforts (DHS, 2005). Despite these Herculean efforts though, a small fraction of the many millions of people affected by the storm still

became sick. Specifically, the CDC reported approximately 20 clusters of diarrheal illness in evacuation centers and 1000 individual cases (Infectious Disease, 2005).

Less dramatic but more common is the unintentional contamination of the water source by storage tanks, septic systems, landfills, fertilizer applications, or industrial facilities. This is no small problem for communities and industry; particularly the Air Force. For example, the U.S. Air Force alone has identified more than 2,500 sites with contaminated ground water for which it is responsible. These sites account for a large portion of approximately $20 billion spent by the Department of Defense on environmental restoration (GAO, 2005). Many of the same kinds of groundwater contamination problems can be expected overseas (AFTTP3-42.2, 2004).

Having a clean source is not enough to make sure the water is clean for use. Many aspects of the distribution system are important to maintaining sanitary water. For example, are sewer lines buried adjacent to potable lines? Does the system maintain positive pressure continuously? Do operators isolate sections appropriately when performing maintenance? Is the system designed with dead legs? All of the above aspects are worthy of careful consideration, planning, and execution.

One particularly insidious aspect has to do with cross-connections to unsanitary systems, such as sewer, fire suppression, chemical tanks, and even sprinklers (USEPA, 2002). Connections can be made safely to such systems if the appropriate backflow prevention devices are installed and maintenance of these is performed as necessary. A backflow can happen whenever hydraulic conditions (i.e., pressure, often referred to as "head") within the distribution system are *different from normal* and cause water to flow backward, opposite the intended direction. Sometimes the backflow is caused by

"backsiphonage" or "backpressure" (USEPA, 2002). A simple example of a potentially fatal backflow is a garden hose submerged in a bucket containing pesticides. If the pressure in the water lines leading to the garden hose drop, which can be caused if someone in the loop demands a large quantity of water, pesticide can backsiphon into the potable water system, potentially killing users. The same result can occur if the hose is connected to a pressurized tank of pesticide (USEPA, 2002). Fortunately, few (i.e., four in 1995) cases of illness are caused by backflow in the United States (Levy, 1998). Overseas, however, the likely absence of a carefully engineered and tested backflow prevention system can be a critical health consideration.

Water may be clean at the source and throughout the distribution system but become contaminated at the point of use. This is why the Air Force requires special surveillance of the aircraft watering points (AFI48-144, 2003). Although Linschoten does not identify the cause of the illness in the following statement, the effect on the mission underscores the importance of safe water for aircrews:

> In late September 1990, during Operation DESERT SHIELD, a RIVET JOINT mission was scrubbed and [Airborne Battlefield Command Control and Communication] was knocked to 50 percent combat effectiveness for a week. Surveillance coverage was lost, seriously degrading the mission. The aircrews were laid up in bed, the result of unintentional food and water poisoning.
>
> —Major Mike Linschoten
> Electronic Combat (EC) Coordinator, CENTAF EC Cell
> (Hickman, 1999)

If such a relatively small, unintentional event can significantly disrupt military operations; no doubt a deliberate, well-planned, and executed threat can do far more.

2.1.2 Deliberate/intentional Contamination or Disruption

"Deliberate chemical and biological contamination of water supplies is common in history" (Hickman, 1999). Often, the tactic has been to disrupt the water supply rather than to contaminate it. Either way it may directly or indirectly affect the outcome of military operations. Examples of both types of tactics, performed either by military forces or terrorists, are shown in Table 2-1 for activities through World War II and Table 2-2 for activities since 1970. Some of these examples are briefly discussed in the paragraphs following the tables. The point to be made from the tables and this discussion is that water has always been a target.

Table 2-1. Water Threats from Ancient Times through World War II

Year	Description
590 B.C.	During the siege of Cirrha, Solon of Athens is said to have used hellebore roots (a purgative) to poison the water in an aqueduct leading from the Pleistrus River (Sidel, 1997).
300 B.C.	Romans buried some of their aqueducts 50 feet underground out of concern an enemy might neutralize their supply (Hershel, 1973).
60 A.D.	Nero preferred using cyanide, the primary toxic compound found in cherry laurel, when he needed to poison enemies or family members (Sidel, 1997).
1155	Frederick Barbarossa, a Roman Emperor, had dead bodies placed in enemy wells as carriers of biological agents (Sidel, 1997).
1503	Leonardo da Vinci and Machiavelli planned to divert the Arno River away from Pisa during a conflict between Pisa and Florence. This bold plan required laborers to excavate about one million tons of earth. Fortunately for Pisa, the lowest bidder was chosen for the job, shortcuts were taken and the plan failed (Honan, 1996).
1942	Nazi's planned "Operation Pastorius" to attack the water distribution systems of the United States (Griegg, 2003).
1943	British scientists develop bomb for the purpose of destroying German dams (Simscience, 2003).
1937-1945	Japanese used biological agents to poison food and water in at least 11 Chinese cities (Atlas, 1999).

Table 2-2. Summary of Water Threats Since 1970

Year	Description
1970s	A Middle East firm reportedly engaged in developing ways to poison the Jordan River with bacteria (Venter, 1999).
1976-1980	Rhodesian government suspected of using biological agents to contaminate the water supplies of black civilians in Rhodesia and Mozambique (Atlas, 1999).
1985	A survivalist group calling themselves the "Covenant Sword and Arm of the Lord" acquired 30 gallons of potassium cyanide with the intention of contaminating the water systems in Chicago and New York, or Washington D.C. (Tucker and Sands, 1999; Beering, 2002).
1986	Plutonium was found in the New York city drinking water system. Though the concentrations were significantly below the toxicity threshold, the occurrence was suspicious (Clark and Deininger, 2000).
1987	An unknown terrorist group killed 19 police recruits on the Philippine island of Mindanao by poisoning their water supply with a pesticide (Tucker and Sands, 1999).
1989	The South African government attempted, unsuccessfully, to contaminate a refugee camp's water supply with cholera and yellow fever producing organisms (Atlas, 1999).
1990	The Defense Intelligence Agency (DIA) received reports that the Iraqi Intelligence Service planned to poison bottled water used by U.S. Military forces stationed in Saudi Arabia. The plan involved buying water from Lebanese companies, poisoning it and re-labeling the bottles with the brand of the U.S. Military's supplier (Haimes et al., 1998a; DIA, 1990).
1992	Kurds poisoned Turkish Army water tanks near Istanbul with potassium cyanide (Karasik, 2002).
1994	Khmer Rouge forces in Cambodia poisoned streams and ponds near the city of Pailin killing at least a dozen Khmer Royal Armed Forces (Karasik, 2002).
1995	Fecal contamination found in bottled water supplied to U.S. military in Somalia. The bottled water was from an approved source (Venter, 1999).
1998	Osama Bin Ladin spoke of poisoning water mains to ensure the United States would "take notice" (Bodansky, 1998).
2002	Italian police arrested nine Moroccans for plotting to poison the water supply of the U.S. Embassy in Rome (AP, 2002).
2003	Cyanide was detected in a bulk water shipment to a U.S. military base in Kuwait. (CENTAFBEE, 2003).

An example of military action to disrupt water supplies is the efforts of Leonardo da Vinci and Machiavelli when they planned to divert the Arno River away from Pisa during the 1503 conflict between Pisa and Florence (Honan, 1996). This bold plan required laborers to excavate about one million tons of earth. Fortunately for Pisa, the lowest bidder was chosen for the job, shortcuts were taken and the plan failed. During the revolutionary war, the Hessians and English were more successful when they destroyed the water system of New York (Thatcher, 1827).

Examples also exist from the terrorist perspective. For instance, on October 2, 2002, a group claiming to be the Earth Liberation Front, an environmental terrorist organization, threatened to destroy two water tanks at Winter Park, Colorado (Crecente and Maziarz, 2002). In June 2005, insurgents destroyed water mains in Baghdad. While piped water service was restored to most of the affected area within a week, other areas needed tanker deliveries to supply water. Then in July 2005, the insurgents destroyed the power supply for a water plant north of Baghdad. These two attacks affected an estimated one million people. Some of the city's populace switched to bottled water and others to digging wells. Out of desperation though and preferring to drink bad water rather than die if thirst, others began to draw water directly from the river (UN, 2005).

In addition to the disruption of water supplies, many poisons, mostly chemical or biological, have been used throughout the years in both politics and war. Nero preferred using cyanide, the primary toxic compound found in cherry laurel, when he needed to poison enemies or family members (Sidel, 1997). Nero had a special advisor on poisons, a woman named Locusta, who may have been the first to systematically study the use of poisons under state sponsorship. For her experiments, she used animals and convicted

criminals. Roman jurists later declared “Armis bella non venenis geri” to indicate that war is waged with weapons, not with poison.

One of the more common methods of poisoning wells was to use dead bodies as carriers of biological agents. Frederick Barbarossa, a Roman Emperor, used this tactic at the battle of Tortona in 1155. During the U.S. Civil War, the confederate army, while retreating in Mississippi, left dead animals in ponds and wells to deny safe water to the advancing Union troops (Sidel, 1997). Some have tried more sophisticated biological agents. In 1970, a group of anti-war communist revolutionaries calling themselves “The Weathermen” allegedly tried but failed to get biological weapons from Fort Detrick, Maryland, for the purpose of contaminating water supply systems in U.S. cities (Carus, 1998).

2.2 Water Security

Since 2001, a number of events have contributed to what the draft Water Vulnerability Assessment guide (2006) calls a “national sense of urgency” to protect our domestic water systems. These include the attempted attack on the United States Embassy water supply in Rome (AP, 2002), the theft of 10 tons of cyanide compound in Mexico (CNN, 2002), and the discovery that our enemies kept diagrams of U.S. domestic public water facilities (Bush, 2002). Given the diverse nature of these representative threats, how does one protect its water supplies? As with most hazards, the countermeasures include a combination of administrative and engineering controls with personal protective equipment (PPE) as a last resort. In the case of water security, the administrative controls include all applicable laws, regulations, policies, and assessments.

Engineering controls include all physical security aspects of the water system (e.g., fences, locks, pressurization, backflow prevention devices, cameras, lights). Treatment systems (e.g., ROWPU and special nuclear-biological-chemical filters) are analogous to PPE because they are implemented as a final step before personal exposure and are only effective against the specific threats for which they were designed. The following sections briefly discuss various aspects of policy and then examine each of these countermeasures.

2.2.1 Security Policy

Air Force water policy is driven by a number of governmental regulations (federal, state and local) and industry standards. Prior to 2002, these regulations and standards were focused on safety issues and protecting water from unintentional threats. Safe drinking water regulations originated in 1974 with the Safe Drinking Water Act (SDWA), which did not seriously consider sabotage. Since 9/11 and in light of threats against our domestic water systems, the SDWA was amended in 2002 with the passage of the Public Health Security and Bioterrorism Preparedness and Response Act to address "Terrorist and Other Intentional Acts." The Act established a requirement and provided funding for community water systems serving populations greater than 3,200 persons to conduct water vulnerability assessments specifically for terrorist and other intentional acts, required the same to develop emergency response plans and provided additional funds for basic security enhancements (e.g., installation of intrusion detection systems, fences, lighting, security cameras, tamper-proofing manhole covers, fire hydrants, and valve boxes).

Air Force water security policy is governed by three programs which overlap. These are the Critical Infrastructure Program (CIP), the Antiterrorism/Force Protection (AT/FP) program and the Safe Drinking Water (SDW) program. The following sections discuss the standards for clean water, assessing vulnerabilities, and providing for contingencies; which taken as a whole comprise the administrative function of water security.

2.2.1.1 Potable Water Standards

Potable water standards refer to drinking water quality standards. In the United States, these are set by the Environmental Protection Administration (EPA) for tap water and the Food and Drug Administration (FDA) for bottled water (because it is considered food). At overseas locations, the Air Force follows the Overseas Environmental Baseline Guidance Document (OEGBD) or the Final Governing Standards (FGS) since the federal and state regulations are not binding but may be used as a goal.

A key part of the EPA requirements for drinking water is a list of maximum contaminant levels (MCLs). At overseas locations, it is Air Force policy (CENTAF/SG, 2005) to first comply with the OEGBD and interim Air Force Manual titled *Sanitary Control and Surveillance of Field Water Supplies* (AFMAN(I) 48-138, 2003) and then try to meet EPA standards whenever possible. The standards set forth in the interim AFMAN(I) 48-138 set limits for a shorter list of contaminants than specified by the EPA. These field standards are more stringent for long-term exposure than for short-term exposure, simply because some contaminants are unlikely to cause adverse health effects if the exposure time is short. The Air Force field standards are considered requirements

for field commanders (AFMAN(I) 48-138, 2003). For a list of references and supporting information related to water quality, see Appendix A (AFMAN (I) 48-138, 2003).

Since bottled water is regulated as “food,” it must meet standards set forth by the FDA. Since FDA regulations do not apply overseas, the Department of Defense policy is to purchase water only from suppliers approved by the United States Army Veterinary Corps. In rare circumstances, when a base cannot procure water from an approved source, there is a provision which allows the local preventive medicine offices to approve local sources (AFI48-144, 2003). However, one must be mindful that there have been recent incidences where locally approved vendors have attempted to sell contaminated water to U.S. forces (ATTFP3-42.2, 2004).

2.2.1.2 Water Vulnerability Assessment (WVA)

As part of the 2002 amendments to the SDWA, the EPA now requires community water systems, including military installations, to conduct water vulnerability assessments (WVAs), which are administrative countermeasures to mitigate intentional threats. Their stated purpose is “to help water systems evaluate susceptibility to potential threats and identify corrective actions” (USEPA, 2006). With the primary focus including vandalism, insider sabotage, and terrorist attack, these assessments should result in specific recommendations to measurably reduce risks by reducing vulnerabilities or consequences. Generally, these recommendations will improve deterrence, delay, detection, or response capabilities. This may be in the form of physical measures (i.e., system or security upgrades) or policies and procedures.

The Air Force was conducting WVAs in both stateside and overseas locations long before they were required by the EPA. Within the Air Force, there are two different organizations that perform water vulnerability assessments. The Security Forces' Anti-Terrorism and Force Protection (AT/FP) office conducts a full spectrum vulnerability assessment (e.g., kidnappings, water sabotage, car bombs, etc.) in accordance with Air Force Instruction 10-245 (which supersedes AFI 31-210). Additionally, the Bioenvironmental Engineer (BEE) conducts an assessment focused only on potable water. The two assessments may be redundant or complementary depending on the level of cooperation between the functions. The 2006 WVA guidance for the BEEs (AFIOH, 2006) recommends a hazard avoidance-based approach called Hazard Analysis and Critical Control Point (HACCP). This approach holds that avoidance is practical and effective where other methods (e.g., contamination detection, early warning, and treatment) are not.

2.2.1.3 Water Contingency Plan

The base civil engineer (BCE) receives recommendations from both the AT/FP and BEE vulnerability assessments, fixes what can be fixed and mitigates what cannot. The BCE is responsible for maintaining a Comprehensive Response Plan (CRP) at all installations, both stateside and overseas, to "ensure adequate resources are available to store and distribute potable water in a contingency situation" (AFI 10-246, 2004).

2.2.2 Physical Security

Now that the policies regarding specific security practices (e.g., testing water for listed contaminants and assessing vulnerability) have been discussed, it is time to discuss physical security. The EPA's guidance for water security (EPA, 2006) follows the same basic assumption as the Air Force WVA guide (AFIOH, 2006). While detection, early warning, and treatment may be effective against slow-moving contamination (as is often the case with groundwater), they are not feasible for intentional attacks (Byer, 2004). Given the current state of technology, most attacks cannot be property characterized until symptoms present themselves in the emergency rooms and hospitals (Byer, 2004). Therefore, the EPA's guidance focuses on denial of access. As discussed below, the means of denying access follow three security concepts: detect, delay, and respond. A final, not recommended, concept is reliance on treatment which will be discussed as well.

2.2.2.1 Intrusion Detection

Various types of sensors, cameras, and seals, are used to detect intrusion. The most common intrusion sensors use magnetic switches, foil, and glass break detectors. These are not invincible, but it is not practical to install all the intrusion detection devices that one might find at a bank into a field water system. Cameras with night vision are also used in the field; they are primarily intended to augment and enhance patrols by security forces. Security seals are another means of detecting intrusion. They are inexpensive and can provide a high degree of assurance that the food or water behind the seal has not been contaminated since it was last checked.

2.2.2.2 Intrusion Delay

Security barriers, fences, locks, and backflow prevention devices are all examples of ways to delay intruder access. These methods delay but do not prevent access; however, delayed access might improve the chances of detection. Barriers, fences, and locks are simple devices, but their prevalence is a testimony to their value. Backflow prevention devices cause delay too. For example, a potential saboteur would have to locate and study the mechanism in order to devise to find a way to defeat it. Another simple and practical way to delay access in the field is the use of razor wire. In all cases, if the intruder is delayed long enough to detect, then security forces may have time to respond.

2.2.2.3 Intrusion Response

Intrusion detection is usually accompanied by an alarm (silent or audible) that calls for security personnel to respond. Military installations typically have robust response capabilities, especially at overseas locations. Some detections, however, do not require urgent response. For example, consider a broken safety seal on a shipment of food or water. By the time the intrusion is detected, the intruder is probably long gone. Therefore, the only practical response may be to destroy the shipment and notify the appropriate agency of the event.

2.2.2.4 Security by Water Treatment

As Tables 2-3 and 2-4 indicate, treatment processes are designed to remove specific contaminants at specific concentrations. These processes are best used for

treating identified and quantified contaminants in the source water. In some cases, routine treatment methods may defeat the intruder. For example, some historical biological weapons attacks were defeated by the presence of residual chlorine in the water system. However, a deliberate and well-planned attack will likely understand the technological limits of the treatment system and be able to defeat it. Therefore, reliance on treatment alone is not recommended.

2.3 Potable Water System Technologies

Each type of potable water system has predictable capabilities, costs, and security implications. However, in the field, these systems are likely to have unpredictable costs and security issues as well. Although it is not within the scope of this research to predict with accuracy the field performance of these particular systems, a broad overview of expected capabilities, limitations, and costs for conventional and advanced technologies is provided.

2.3.1 Characteristics of Conventional Water Technologies

Conventional technologies refer to any means of providing water that have been widely used. These include conventional drilling, Reverse Osmosis Purification Units (ROWPU), bottled water, compact water treatment units, and conventional water treatment plants. A discussion of advanced water technologies follows the discussion of conventional technologies.

Table 2-3. Treatment Technology Capabilities for Selected Primary Contaminants (Letterman, 1999)

	Conventional Water Treatment				Membrane processes			Ion exchange		Adsorption	
Contaminant Categories	**Aeration and Stripping**	**Coagulation, sedimentation or DAF, filtration**	**Lime softening**	**Chemical oxidation and disinfection**	**Ultrafiltration**	**Reverse Osmosis**	**Electrodialysis/ED reversal**	**Anion**	**Cation**	**Granular activated carbon**	**Activated alumina**
Inorganics											
Arsenic (+3)		XO	XO			X	X	X			X
Arsenic (+5)		X	X			X	X	X			X
Cadmium		X	X			X	X		X		
Chromium (+3)		X	X			X	X		X		
Chromium (+6)						X	X	X			
Cyanide				X							
Mercury (inorganic)			X			X	X				
Nickel			X			X	X		X		
Nitrate						X	X	X			
Nitrite						X	X	X			
Selenium (+4)		X				X	X	X			X
Selenium (+6)						X	X	X			X
Organics Contaminants											
Volatile organics	X									X	
Synthetic organics						X				X	
Pesticides/Herbicides					X	X				X	
Radionuclides											
Radium (226 + 228)			X			X	X		X		
Uranium						X	X	X			
X, appropriate process for this contaminant											
XO, appropriate when oxidation is used in conjunction with this process DAF, dissolved air flotation											

Table 2-4. Treatment Technology Capabilities for Selected Secondary Contaminants and Constituents Causing Aesthetic Problems (Letterman, 1999)

	Conventional Water Treatment				Membrane processes			Ion exchange		Adsorption	
Contaminant Categories	Aeration and Stripping	Coagulation, sedimentation or DAF, filtration	Lime softening	Chemical oxidation and disinfection	Ultrafiltration	Reverse Osmosis	Electrodialysis and ED reversal	Anion	Cation	Granular activated carbon	Activated alumina
Hardness			X		X	X	X		X		
Iron & Manganese		XO	X						X		
Total dissolved solids						X	X				
Chloride						X	X				
Sulfate					X	X	X				
Color		X		X	X	X				X	
Taste and odor	X			X						X	

X, appropriate process for this contaminant
XO, appropriate when oxidation is used in conjunction with this process
DAF, dissolved air flotation

2.3.1.1 Drilling for Water

The military has a continuing need to drill for water. Therefore, this paragraph discusses capabilities, advantages, and disadvantages. The United States military has approximately 28 well drilling units, most being assigned to Army Reserve units. A team of geologists at the U.S. Army Topographic Engineering Center provides consulting services to support these drilling units. They perform hydro-geologic analyses of potential well sites and recommend the most suitable type of drilling equipment. The typical military drilling rig uses mud rotary drilling, air rotary drilling or percussion drilling. With these methods, military drilling units are capable of drilling wells 400 to 600 feet deep and penetrate 1,500 feet with special equipment (Scarborough and Lang, 2001). Additionally, contractors are capable of drilling wells as deep as 5,000 feet

(McDonnell, 1996). The principle advantages of drilling wells lie in the relative security of an underground source, which provides a reliable water supply in case of nuclear, biological, or chemical surface water contamination. The disadvantages include the uncertainties, time, and cost up-front to establish wells. During the first gulf war, some wells took 60 days to drill (McDonnell, 1996). There have been instances where wells were drilled at significant expense and the yield of the well was insignificant. These advantages and disadvantages are summarized in Table 2-5.

Table 2-5. Summary of Well Water Advantages, Disadvantages, and Costs

Advantages	▪ Most secure from chemical, biological, and nuclear surface contamination. Wells can be drilled by military or contractors. ▪ Subsurface water quality tends to be constant so it is amenable to treatment system design.
Disadvantages	▪ Drilling is a hit or miss proposition. ▪ Deep wells may take 60 days to drill (McDonnell, 1996). ▪ Possibility of poor well yield.
Costs	▪ \$28 to \$36 per linear foot (Means, 1996).

2.3.1.2 Reverse Osmosis Water Purification Unit (ROWPU)

This tactical water filtering system uses a well-developed membrane technology (i.e., reverse osmosis) to produce treated water for drinking, hygiene, sanitation, food preparation, and medical support purposes (AFH 10-222, 1999). The filtration unit is normally packaged with a storage and distribution system which usually includes pumps, distribution lines, and storage (e.g., 3,000-gallon “onion” tanks and two 20,000-gallon bladders). Crews require special training to operate and maintain the ROWPU. The

capabilities, advantages, and disadvantages of the ROWPU system are discussed in the following paragraphs.

ROWPU is capable of removing salts, bacteria, proteins, and generally other molecules with a molecular weight greater than 150-250 daltons (Osmonics, 2006). This allows it to remove most organic molecules and 90 to 99% of all ions in a single pass. As such, it is capable of producing potable water from almost any source, including sea water. ROWPU has the additional short-run capability of filtering out nuclear, biological, and chemical (NBC) agents if it is fitted with the NBC filter (i.e., deionization cartridges). The technical specifications require the optional NBC filter to achieve a 99.9% reduction in NBC contaminants for at least for 100 hours (PD04WRLEEG67, 2005). Still, the best defense against NBC agents is to make it difficult for an enemy to access the water source. The following warning to operators comes from the ROWPU handbook (AFH 10-222, 1999).

> "Although not prohibited, think twice before locating water production assets off base where they become more vulnerable."

ROWPU combines the capabilities of reverse osmosis with a rugged platform capable of redeployment as military operations move camps. In summary, ROWPU's primary advantages are flexibility and mobility.

Disadvantages of ROWPU include morale/palatability, a higher frequency of cartridge replacement, and greater power consumption compared to other membrane processes such as nanofiltration and ultrafiltration. Palatability factors, especially taste and temperature, may be its biggest disadvantage. Although the technical water quality is better than most of the municipal water found in the United States, the chlorine necessary

to keep the water sanitary in bulk storage bladders and distribution lines makes the water taste like the water in a typical swimming pool. Even without the chlorine, the taste is strange to some because the water lacks the trace minerals normally found in drinking water. The bulk storage bladders create another problem in sunny desert climates; the resulting hot water is not aesthetically pleasing to drink (Water Demonstration, 2005). Table 2-6 summarizes the previous discussion.

Table 2-6. Summary of ROWPU Advantages, Disadvantages, and Costs

Advantages	▪ Capable of producing high-purity water from most any source including salt water. ▪ System is portable and rugged for military units on the move.
Disadvantages	▪ Primarily aesthetic: high levels of chlorine used to ensure product water remains sanitary, bulk storage imparts a rubbery taste and water is often hot. ▪ Units may be unavailable as they are reserved for advancing troops.
Costs	▪ 0.8 to 1.6 cents per liter (Wyatt, 2002).

2.3.1.3 Bottled Water

What may have started as a wartime expedient and was justified by its convenience and effect on morale in 1990 has become an expectation.

> Soldiers and their commanders demand bottled water and have been drinking large quantities of bottled water since 1991 even though U.S. Army policy stipulates that Soldiers are to drink bulk potable water. (Water Packaging, 2005)

Since bottled water has no capabilities in the same sense as the other technologies in this section, only the advantages and disadvantages are discussed in the following paragraphs.

Bottled water's advantages are convenience and aesthetics. When other methods can take days or weeks to set up, bottled water can be carried in with the first units on the ground. It is also convenient to stockpile cases of bottles in work areas, or put a case or two in the back of a "humvee" (high-mobility multipurpose wheeled vehicle) before heading out on a patrol. The other major advantage is aesthetics. For this research the term aesthetics includes those things that are perceptible to the senses such as taste, odor, and color. People like the taste of bottled water; it typically has no color and is easy to put in coolers.

However, bottled water has significant drawbacks primarily in the areas of force protection, logistics, and cost. Under the best of situations and despite common perceptions, bottled water is not safer than municipal water found in the United States (BWL, 2005). If water bottled in the United States, where it is subject to inspection by the Food and Drug Administration, is not safer than tap water, safety questions are reasonable since most of the approved bottled water in Middle East areas of operation comes from countries such as Turkey, Kuwait, and Jordan (Water Packaging, 2006). Moreover, war is not the best of situations. Recently local vendors have attempted to sell contaminated water to U.S. forces (ATTFP3-42.2, 2004). Compounding this threat are the great distances from vendors to troops which create surveillance problems and makes for substantial logistic trains, including significant force protection concerns for the convoys.

> Nearly sixty percent of our vehicle convoys in Iraq are carrying water. This has become very dangerous in the current fight due to roadside bombs and other attacks. If you can mitigate part of the issue of having to carry water, then [fewer] Soldiers on the road equals [fewer] casualties. (Water Packaging, 2006)

Contract costs of bottled water vary considerably from local market to local market but can range from \$0.10 to \$1.50 per liter and average 52 cents per liter (Wyatt, 2002). However, purchase price and shipping represent only part of the costs associated with bottled water. True costs must include the manpower required to support transportation and security requirements, but obtaining true costs is beyond the scope of this thesis. Fortunately specific cost analyses for specific locations are not necessary for testing the model in this thesis. Instead it is sufficient to assume that in most instances the "monetary costs and the sustained logistical burden of procuring, transporting… [bottled water] is far more costly than drinking water produced by ROWPU" (Use, 2003). A summary of advantages, disadvantages, and costs is given in Table 2-7.

Table 2-7. Summary of Bottled Water Advantages, Disadvantages, and Costs

Advantages	▪ Acceptance is high-because of taste, convenience, and false perceptions of health/security.
Disadvantages	▪ Logistical difficulties. ▪ Security is problematic. ▪ Cost is usually higher than all other alternatives.
Costs	▪ Varies widely but usually from \$0.20 to \$1.50 per liter.

2.3.1.4 Compact Water Treatment Units

These commercial versions of the military ROWPU have been installed by the Army Corps of Engineers as well as various humanitarian agencies throughout Iraq. This section discusses the capabilities, advantages and disadvantages of this technology. Like ROWPU, they require specially trained personnel to operate and depend on electrical power and replacement parts (e.g., cartridges). Because they are based on the technology of reverse osmosis, they should be able to produce water of similar quality as that of ROWPU. The additional advantages of using commercial units include rapid procurement and setup, as well as competition among suppliers in a free market. A particular advantage of compact units over conventional water treatment is that they can be dispersed so that the enemy would unlikely destroy more than one in a single attack. (Note: This same advantage for civilian application can be applied to expeditionary bases). The disadvantages are aesthetics just as with ROWPU. Table 2-8 summarizes the advantages, disadvantages and costs associated with Compact Water Treatment Units.

Table 2-8. Summary of Compact Water Treatment Units

Advantages	▪ Capable of producing high-purity water from most any source including salt water. ▪ Initial costs probably much less since system is not ruggedized for the military. ▪ Advantages of competitive pricing are exploitable since these are available from many suppliers.
Disadvantages	▪ Disadvantages same as for ROWPU if using the same storage bladders (primarily aesthetic): high levels of chlorine, rubbery taste, and temperature often hot.
Costs	▪ 0.7 cents per liter (Frenkel, 2004), which is less than ROWPU as might be expected.

2.3.1.5 Conventional Water Treatment Plants

"Conventional" refers to all technologies commonly used in the United States to purify water for drinking purposes. These include coagulation, sedimentation, air stripping, dissolved air flotation, sand-bed filtration, and lime softening (Letterman, 1999). Membrane processes are excluded because they have already been discussed and, although they are being used more widely for municipal water systems, are still somewhat rare. The following paragraphs discuss the capabilities, advantages, and disadvantages of conventional water treatment processes

Conventional water treatment is capable of treating for a variety of contaminants and undesirable constituents (See Table 2-3 and 2-4). The quality of the source water determines which processes are necessary and whether conventional treatment methods are adequate. For example, waters contaminated with lead, nitrate, nitrite, or synthetic organics cannot be treated by conventional means and may require reverse osmosis (Letterman, 1999).

The advantages of conventional methods include low operating costs and high quality which usually exceeds that of bottled water. Typically, tap water is the least expensive supply, usually costing 5 to 15 cents per thousand liters (GE Osmonics, 2006), which makes it roughly a thousand times less expensive than bottled water. Often, water treated by conventional processes tastes better than bottled water (Stossel, 2005).

The disadvantages may be high construction costs if the source water requires extensive treatment. Because of this, it may take years of operation to justify the initial expense. The construction costs may be justifiable if "salvage value" can be accounted for when the assets are turned over to civilian populations after the military operations are

over. Larger water treatment plants are more economical on a unit production basis but are contrary to the dispersal of assets objective. However, if the raw water quality is sufficient, minimal conventional treatment may be necessary. Small water plants consisting of sand filters and chlorinators may be all that is necessary if the source of water is good. This is often the case when military drilling units install wells for humanitarian missions in places such as Guatemala, Haiti, or Honduras. Table 2-9 summarizes the advantages, disadvantages, and costs of conventional water treatment.

Table 2-9. Summary of Conventional Water Treatment

Advantages	▪ Capable of consistently producing water to meet the highest EPA standards, depending on the source water quality. ▪ Capital assets may be turned over to local civilian authorities as part of reconstruction efforts. ▪ Minimal treatment may be necessary if the raw water quality is sufficient.
Disadvantages	▪ Typically units are large, which is at odds with dispersal objective. Note: this is not the case if the water source permits minimal treatment. ▪
Costs	▪ 10 cents per thousand liters (GE Osmonics, 2006).

2.3.2 Characteristics of Advanced Water Technologies

Advanced water technologies refer to means beyond what is normally considered. They are novel and offer certain capabilities or advantages over conventional technologies. These include deep drilling, directional drilling, ultrafiltration, field bottling, and advanced detection. These advanced technologies are discussed in the following sections.

2.3.2.1 Advanced Drilling

Advanced drilling may produce water when conventional wells fail due to low soil permeability or extreme depth to the water source. Typically, military well-drilling detachments can drill 400 to 600 feet and as deep as 1,500 feet with additional special equipment. However, "Geography and drilling history supports the need to go much deeper… to over 5,000 feet" (Scarborough et al., 2001). As mentioned earlier, some contractors can drill to 5000 feet.

When the market price of potable water exceeds the price of crude oil, the situation suggests consideration of the advanced methods developed by the oil industry such as directional drilling and remote drilling. Oil companies can drill into formations that are five miles away using directional drilling (SPE, 2006). This lets the drilling team locate the well head inside a secure base and still reach fresh water, which may be deep underground and a significant distance outside the base perimeter. Remote drilling enables crews to monitor and guide drilling operations from halfway around the world (SPE, 2006). Remote drilling may alleviate some of the problems of manning operations during military offensives. Some of these oil well techniques may be adaptable to water

well drilling. A summary of the potential advantages and disadvantages is given in Table 2-10.

Table 2-10. Summary of Advanced Well Drilling

Advantages	▪ Well water is more secure from chemical, biological, and nuclear surface contamination. ▪ Subsurface water quality tends to be constant so it is amenable to treatment system design. ▪ The chances of striking water are greater and less dependent on the well-head location than is the case with conventional drilling.
Disadvantages	▪ Unproven. ▪ Drilling is still a hit-or-miss proposition. ▪ Drilling time may be longer.
Costs	▪ Costs probably exceeds the $28 to $36 per linear foot for conventional drilling (Means, 1996)

2.3.2.2 Advanced Purification

The application of membrane filtration has improved substantially, to the point that it is now economical to purify municipal water using ultrafiltration (Ultrafiltration, 2000). Ultrafiltration is capable of turning muddy water into water of pharmaceutical grade. It has certain advantages, disadvantages, and costs associated with it.

The primary advantage of ultrafiltration is that it provides most of the capability of ROWPU at a reduced operating cost. Since it rejects larger particles (0.1 micron), it can operate at much lower pressures (10 to 100 psig) and requires much less energy to operate the pumps (Osmonics, 1996). Even though it does not remove salts, it is capable of rejecting most of the contaminants of concern including organics, bacteria, and viruses (Osmonics, 1996). Although it relies on cartridges as does ROWPU, these cartridges are not replaced as often which lowers operating costs and the logistical burden to supply a remote location.

The primary disadvantage is that it does not remove salts, therefore, it cannot provide drinkable water from a saltwater source. Even with this limitation, most deployment sites could still use this technology. Additionally, unless the Department of Defense requests a ruggedized version, ultrafiltration units are likely to be less mobile and less rugged than ROWPU. Table 2-11 summarizes the advantages, disadvantages, and costs of ultrafiltration.

Table 2-11. Summary of Ultrafiltration

Advantages	▪ Capable of producing high-purity water from most any source other than salt water. ▪ Initial costs are probably less since system is not ruggedized for the military. ▪ Advantages of competitive pricing are exploitable since these are available from many suppliers. ▪ Less demand on the petroleum logistics since power requirements are much less.
Disadvantages	▪ Disadvantages same as for ROWPU if using the same storage bladders (primarily aesthetic): high levels of chlorine, a rubbery taste and temperature often hot. ▪ Probably not as mobile as ROWPU.
Costs	▪ No source found, however the costs are likely to be significantly less than ROWPU. ▪ Assume: 0.4 cents per liter

2.3.2.3 Advanced Packaging

A common problem to all of the treatment processes discussed above is the shortcomings of the field water storage and distribution system. The system of hoses and storage bladders used to store the product water of the ROWPU filtration system and the chlorine addition requirement affects the taste of the water enough to make it a morale

issue**.** To address this, the Army is developing a deployable water bottling plant, which provides the force protection and logistical benefits of ROWPU without the aesthetic drawbacks associated with the standard ROWPU concept. A demonstration of this new concept was held in December 2005 at the Army Materiel Command (AMC) headquarters in Fort Belvoir, Virginia. The following paragraphs describe the capabilities, advantages, and disadvantages of the Army's innovation.

The "tactical water packaging concept" can fill disposable Camelback ® bladders at a rate of 10,000 to 12,000 one-liter bags per 8-hour shift or 14,000 one-liter screw cap bottles in a 20-hour day. The field requirements include resupply of bottles or bags, manpower, and electricity. The volume and mass of resupply is much less than that of bottled water because the bottles come in "preforms." They are much shorter and thicker than the filled bottles and look somewhat like test-tubes. Preforms are warmed and then expanded during the bottling process just prior to filling and capping

The advantages of this concept are primarily logistic, aesthetic, and convenience. Resupply efforts are much reduced because the preforms are much smaller and weigh much less than filled bottles of water. The resupply advantages of the disposable Camelback ® bladders are greater still. Because these packages are well sealed, they do not require the high chlorine concentration needed for bulk water storage and distribution. It is also feasible to add some of the minerals normally found in tap and bottled water so it does not taste like distilled water. The smaller sizes are more convenient for the user and can be stored in coolers which make the water much more palatable. The tactically packaged water offers one more advantage over commercial bottled water: it is purified by reverse osmosis, the best available technology, which is seldom the case with

commercial bottled water. The disadvantages are that it is unproven in the field, not yet available, and requires additional manpower and energy compared to ROWPU. A summary of the advantages, disadvantages, and cost is provided in Table 2-12.

Table 2-12. Summary of Field Bottling

Advantages	▪ Material imparts no rubber taste. ▪ Sanitary seal permits much lower chlorine requirement, which improves taste. ▪ Smaller packages may be stored in coolers, improving palatability. ▪ Smaller packages are more convenient for troops to carry. ▪ Many small packages sealed by military personnel provides greater dispersal of assets without the risks normally associated with commercial bottled water.
Disadvantages	▪ Unproven ▪ Requires some military personnel. ▪ Requires some resupply of preforms or disposable liners. ▪ Litter from bottle waste.
Costs	▪ Unspecified. Probably less than most bottled water. ▪ Assume: 20 cents per liter including materials and cost of ROWPU filtration. Actual costs may be lower.

2.3.2.4 Advanced Detection

At the present time, sensor technology is not capable of detecting the wide variety of chemical and biological agents that might be used to contaminate water (NRC, 2002). Although laboratories can perform all types of analysis, it is nearly impossible to sample for *all* suspect agents continuously, ship samples to capable laboratories, and get results back in time to take action. Until sensor technology is much more advanced, the best strategy is to protect the water from enemy access.

2.4 Field Water System Selection

The expeditionary air base commander must chose between imperfect alternatives involving tradeoffs regarding which method will be used to provide potable water on his or her base. Multiple organizations have a stake in the decision and, since some alternatives will be more burdensome to some organizations than others, there will likely be a tendency to defend one's organizational interests. Clemen (1996) would characterize this as a "hard decision" because it is complex, involves multiple objectives with tradeoffs and the best alternative may depend on the perspective of the expert being asked. It calls for a methodology that facilitates constructive discussion among the stakeholders, creation of alternatives, and leads to an objective, repeatable, and defendable ranking of alternatives based on the commander's objectives.

2.5 Decision Analysis

Decision analysis is a discipline of study that helps decision makers make better decisions. The application of decision analysis theory gives the decision-maker a better understanding of the problem, thereby facilitating a better decision. The following paragraphs discusses the normal method of decision making before offering a better method, one which will be used in this research.

The traditional and easiest approach to making a decision, according to Kenney (1992), is to "focus narrowly on an obvious set of alternatives and select one." Kenney calls this "Alternative Focused Thinking" and offers a new approach which is not "anchored" to alternatives but is based upon focusing deliberately on what is valued. He

calls his approach “Value Focused Thinking.” The basic difference is the sequence of activities listed in Table 2-13.

Table 2-13. Alternative vs. Value-Focused Thinking (Kenny, 1992)

Alternative-focused thinking	Value-focused thinking
1. Recognize a decision problem	1. Recognize a decision problem
2. Identify alternatives	2. Specify values
3. Specify values	3. Identify alternatives
4. Evaluate alternatives	4. Evaluate alternatives
5. Select an alternative	5. Select an alternative

Alternative-focused thinking makes the key mistake of eliminating alternatives for the sake of progress (Keeney, 1992). The exclusion of possible alternatives means, in effect, that the decision maker is not selecting the best alternative, but the “least-worst alternative” (Weir, 2005). However, it could be that the “best of the worst” alternative does a very poor job of satisfying the objectives since the decision is often based on how well the alternatives compare to a “favorite” without consideration of fundamental objectives (if they are understood) or the decision maker’s values (Kenney, 1992). In other words, values are what the decision maker cares about; since they are more fundamental to the decision than alternatives and should be the basis for decisions, they should be defined before alternatives are identified (Keeney, 1992). As shown in Figure 2-1, Kenney (1992) illustrates the central role of values in his methodology by placing it in the center of a figure surrounded by derived advantages, which are further described in Table 2-14.

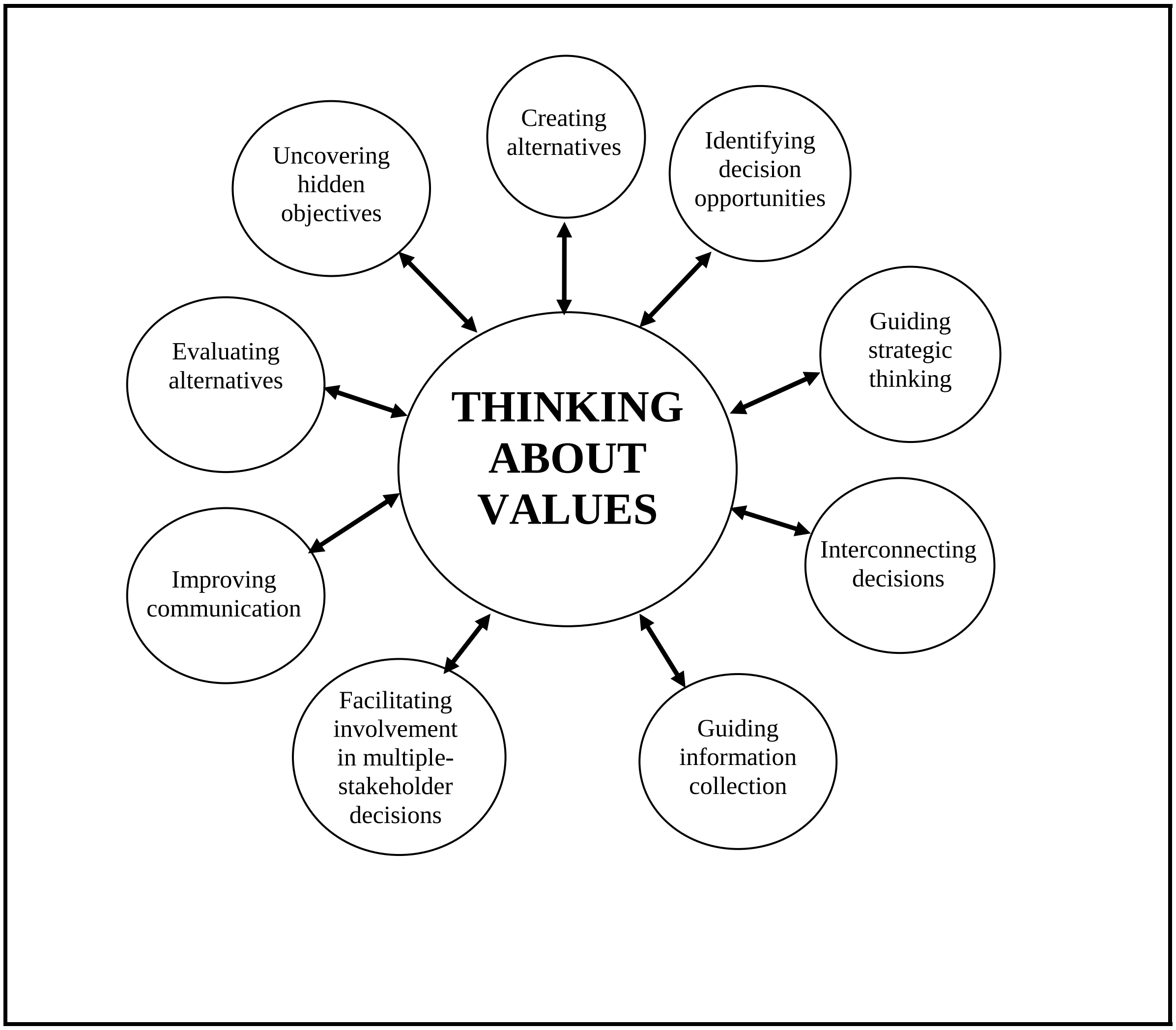

Figure 2-1. Advantages of Value-Focused Thinking (Kenney, 1992)

Table 2-14. Advantages of Value-Focused Thinking (Kenney, 1992:24)

Advantage	Description
Uncovering hidden objectives	If any stakeholder has hidden objectives it is more difficult to come up with solutions that are going to meet those objectives.
Guiding information collection	Identifying the values up-front means one need only to collect the information that helps one achieve those values.
Improving communication	"For most… problems, values, rather than facts, are the aspect of the problem about which many members… will have knowledgeable viewpoints. Discussion of the details of the consequences of various alternatives often depends on technical and complex concepts from various professional fields" and can be worked outside of the committee." (Keeney, 1994: 25)
Facilitating improvement in multiple-stakeholder decisions	"Many decisions…involve multiple stakeholders who must interact to produce decisions." Discussion of values forges an agreement of what is important. "In situations with controversy, a common understanding about what are important evaluation considerations may provide a better basis for compromise and/or consensus with regard to selecting alternatives." (Kirkwood, 1997: 23)
Inter-connecting decisions	Different problems will have different specific objectives but if the specific objectives are based on consistent strategic objectives, then the solutions should not work against each other.
Evaluating alternatives	When the values are built into a value model it is "possible to derive implications for the relative desirability of the alternatives. Furthermore, sensitivity analysis of the relative desirability of these alternatives to specific value judgments, as well as to specific factual data can be made." (Kenney, 1994:26)
Creating alternatives	"It may be much more important to create alternatives than to evaluate already available ones. The creativity necessary to design new alternatives is often neglected by decision methodologies." (Keeney, 1994: 26)
Identifying decision opportunities	Typically we see a decision opportunity when we are "disenchanted" with something or we "perceive possibility to do something better." But to "systematically [appraise] how well we are doing in terms of our values may suggest fruitful decision opportunities to formulate and pursue." (Keeney, 1994: 26)
Guiding strategic thinking	Because the values are explicitly stated, they can be helpful in cross-checking the strategic objectives. "Stating strategic objectives very clearly and unambiguously can give you a stable point of reference to guide all of your decision making for a long time. It is a very sound place to begin your thinking when faced with a situation in which you don't even know where to begin." (Keeney, 1994: 28)

VFT does not replace judgment on the part of the decision maker (Weir, 2005), but when applied properly it can help the decision maker form a better understanding of the objectives and tradeoffs. The decision maker should be able to clearly articulate the reasons for selecting a particular alternative and how well that alternative meets the organization's objectives (Weir, 2006). VFT may be most useful in guiding the search for better alternatives because it is not anchored to a limited set of alternatives as is the case when evaluating alternatives in the traditional fashion (Kenney, 1992).

Value focused thinking (VFT) is used widely in industry, government and the military. Government applications include: the siting of energy facilities (Keeney, 1980), performance measures for radioactive waste remediation (Kenney, 1996) and choosing the best aircraft (manned or unmanned) for border security operations (Weir, 2006). Additionally, the military uses VFT for an increasing number of complex decisions, such as determining which bases to close (Base Realignment and Closure process) and which programs to fund (Capabilities Review and Risk Assessment) (Weir, 2006).

2.6. Decision Support Model Framework

This research uses the ten-step VFT methodology outlined by Shoviak (2001) and shown in Figure 2-2. The 10 steps are explained in the following sections. The first six steps will be implemented in Chapter 3 and the last four in Chapters 4 and 5.

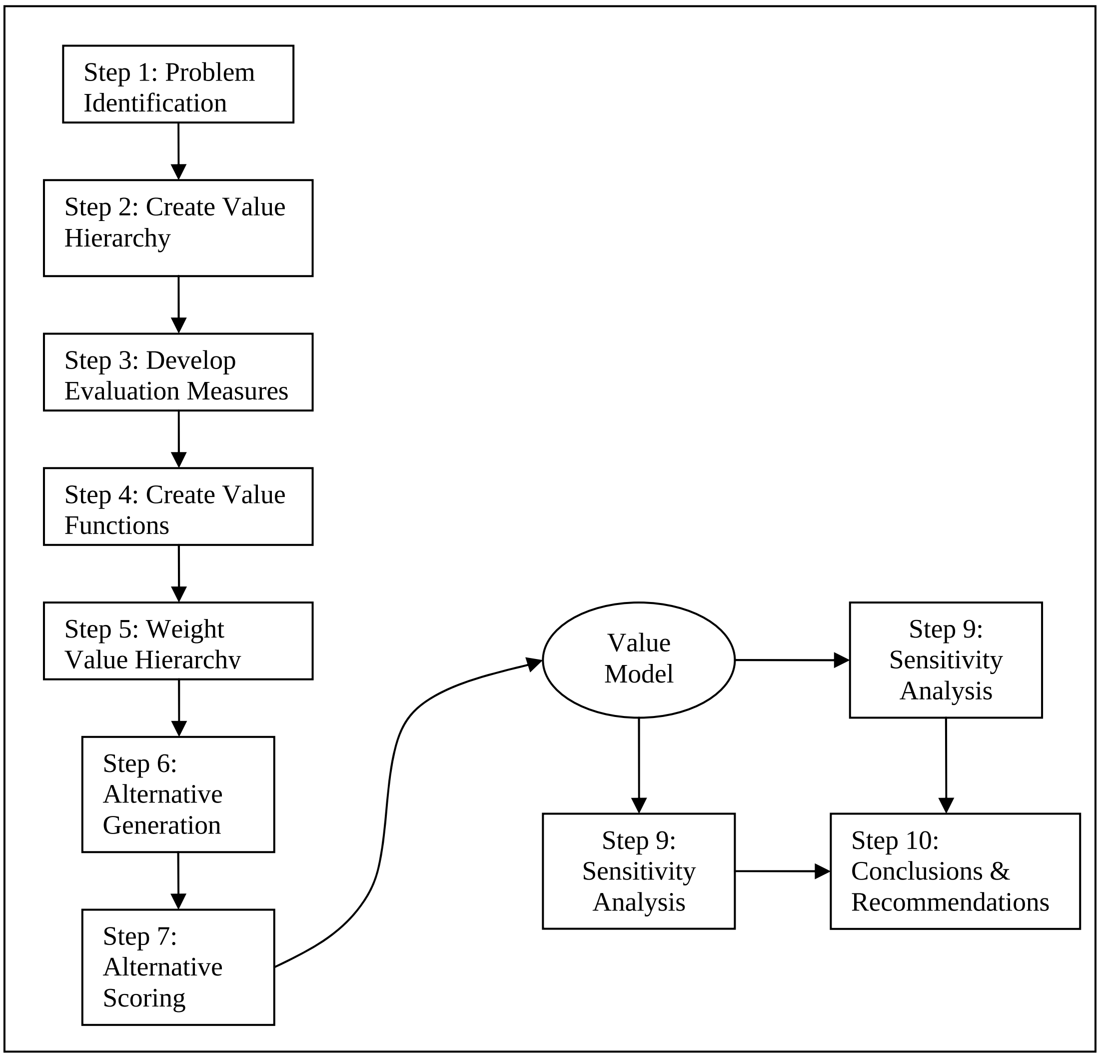

Figure 2-2. Value Focused Thinking Ten-Step Process (Shoviak, 2001)

2.6.1 Step One – Identify the Problem

Much effort will be wasted if the problem is not identified accurately at the start. Therefore, it is well-worth the extra effort at the beginning to ensure the problem is correctly identified. Depending on what is learned during subsequent steps, it may be necessary to come back to this step during the decision making process to revise the problem statement. Incorrectly identifying the problem is called an “error of the third kind” (Mitroff and Betz, 1972). According to Mitroff, “type-III” errors are in the same league as the type-I (false positive) and type-II (false negative) errors from statistics.

2.6.2 Step Two – Develop Value Hierarchy

The value hierarchy is a graphical representation of the decision maker’s values. In a visual manner, it clarifies the values’ relationships to one another, makes it easier to identify any missing objectives and organizes the objectives into independent and quantifiable attributes which permits quantitative modeling. Figure 2-3 provides a generic value hierarchy example with two tiers and two branches. As the figure illustrates, the hierarchy is structured similar to an organizational chart. At the top, or left side depending on orientation, of the hierarchy is the primary objective (decision problem) followed by fundamental objectives. The fundamental objectives are broken down into means objectives and finally, at the ends of the branches, are the measures. Members of a tier are the same distance from the top of the hierarchy, while members of a branch are all the measures and objectives connected to a fundamental objective (Weir, 2004). The complexity or simplicity of the hierarchy is dictated by the complexity or simplicity of the problem.

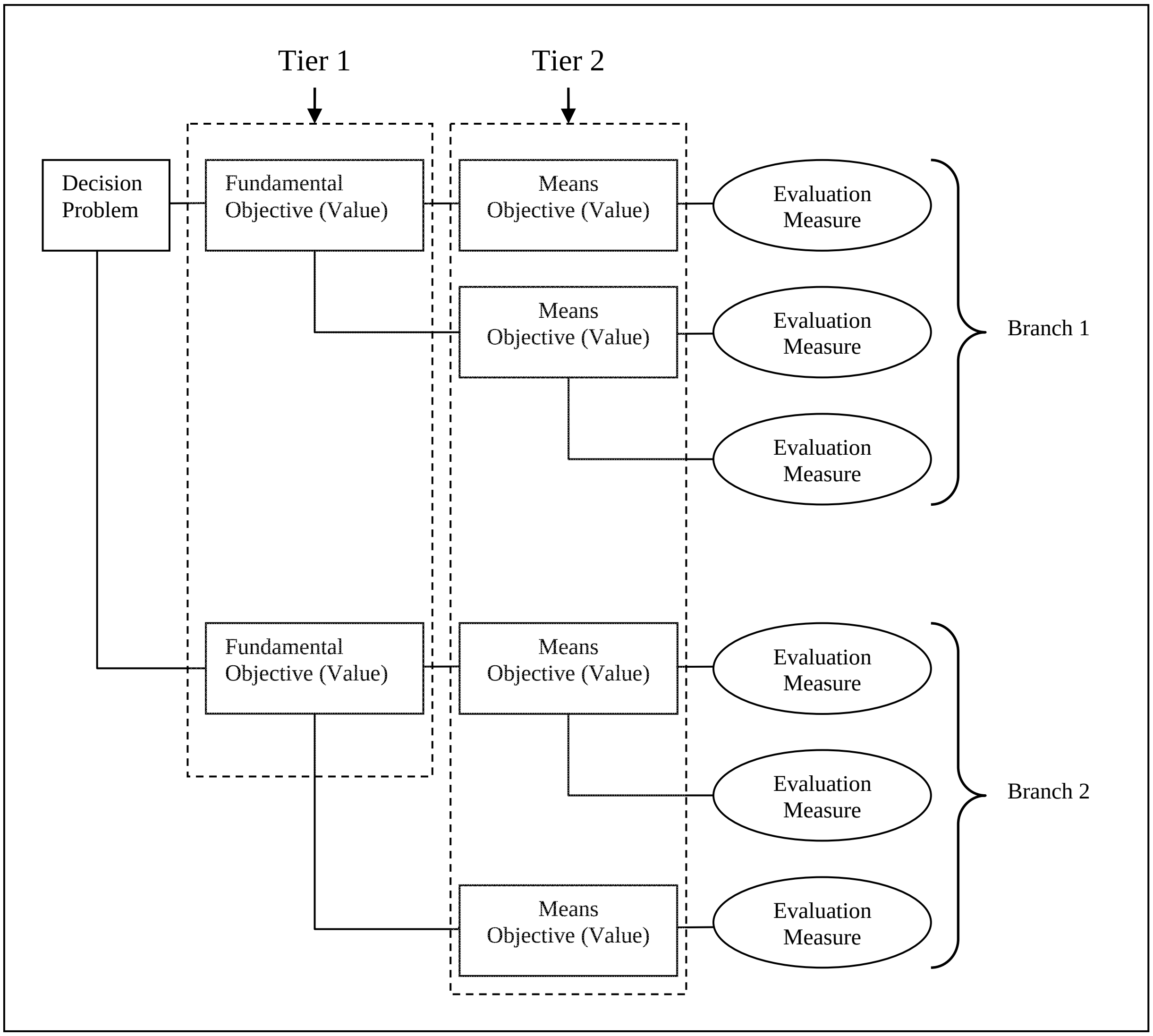

Figure 2-3. Generic Value Hierarchy (Jeoun, 2004)

Many different value hierarchies can be constructed for the same problem. What makes one value hierarchy better than another will be the degree to which it satisfies Kirkwood's (1997) five desirable properties: completeness, nonredundancy, decomposability, operability, and small size. To be complete, a hierarchy must meet two requirements. It should be collectively exhaustive, which means it covers all relevant concerns of the problem and the evaluation measures should adequately grade the degree to which objectives are attained. To be nonredundant, there should be no overlap between any two evaluation considerations in the same layer or tier, which means no measure is double counted. To be decomposable, or preferentially independent, means the importance a decision maker gives one value does not change as the scores of any of the other measures change. Otherwise, the objectives could not be treated separately (Keeney, 1997). To be operable, a hierarchy should be easily understandable to those who will use it. Finally, if everything else is equal, a smaller hierarchy is preferred to a larger one simply because it easier to use the accompanying model (e.g., takes fewer resources to evaluate alternatives) and it is easier to communicate the results.

2.6.3 Step Three – Develop Evaluation Measures

At the end of the hierarchy are the measures, represented in the diagram by ovals. Measures are used to quantify the degree to which an alternative achieves the stated objectives and have either natural or constructed scales. Natural scales are familiar and understandable to everyone (e.g., number of fatalities). Constructed scales are custom designed for the problem because a natural scale either cannot be found or is impractical to implement. A constructed scale may be used when it offers advantages over natural

scales (e.g., easier for non-technical people to understand or defined to avoid a problem of preferential dependence). Constructed scales can become natural scales as people become more familiar with them. For example, the Richter scale for earthquake intensity was originally a constructed scale; but now that people are so familiar with it, one could classify it as a natural scale (Kirkwood, 1996).

Measures can also be classified as direct or proxy. A direct measure is one that directly measures the achievement of an objective. Kirkwood (1997) offers dollars as an example of a direct measure of a common business objective: profit. Sometimes the measure is something which is hard to gauge directly (e.g., the strength of the economy), so proxy measures are useful. Examples of proxy, direct, constructed, and natural measures given in Table 2-15.

Table 2-15. Examples of Evaluation Measures (Staats, 2005)

	Natural	**Constructed**
Direct	Net Present Value Time to remediate Cost to remediate	Olympic Diving Scoring Weather Prediction Categories Project funding Categories
Proxy	Gross National Product (Economic growth) Site cleanup (Time to remediate)	Performance Evaluation Categories (Promotion Potential) Instructor Evaluation Scales (Instructor Quality)

2.6.4 Step Four – Create Value Functions

Value functions, sometimes referred to as single dimensional value functions (SDVF), convert measures used as inputs into value. The value axis ranges from 0 to 1 (by convention) with 0 as the least desirable and 1 as the most. Value functions must be

monotonic (i.e., always increasing or always decreasing over the range of interest). Value functions serve to solve a subtle problem of returns to scale.

The concept of “returns to scale” is borrowed from economics. It holds that an incremental change at the low end of the independent axis rarely produces the same impact as an incremental change at the high end of the independent axis. This can be illustrated by using money as an example. A person who has little money will value an incremental $1000 gift more than a person who has millions of dollars. Conversely, a person who has millions of dollars will be less concerned about losing $1000 than a person who has little money. If returns to scale were not a problem, then one could simply translate measure units into values units using a constant conversion factor.

Value functions can assume a variety of shapes. They can be simple linear functions, exponential, S-shaped, piece-wise linear, or even categorical. They may exhibit the typical returns to scale curve which levels off as the value reaches “saturation.” In other cases, the “curves” are actually steps. A step function may be justified if some process outside the measure is limited in some batch-wise sense. Some examples of value functions are shown in Figure 2-4.

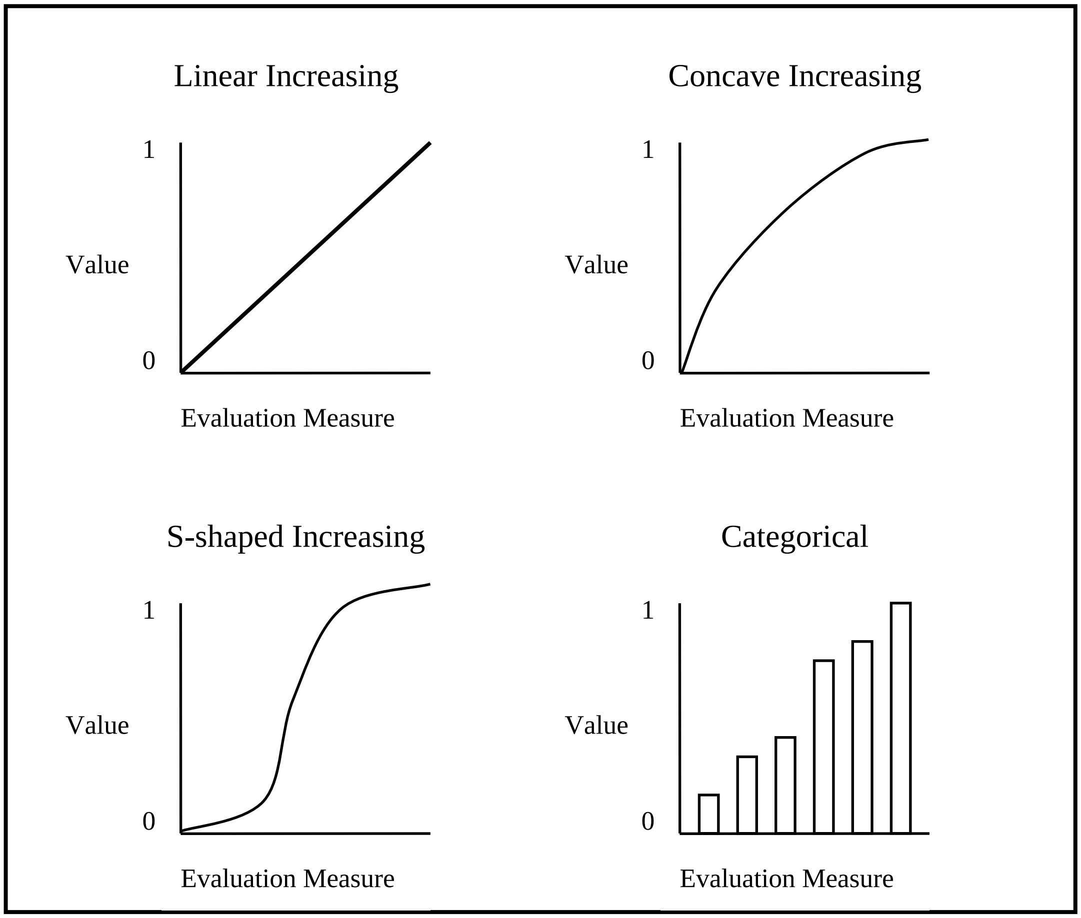

Figure 2-4. Generic Single Dimensional Value Functions (Staats, 2005)

2.6.5 Step Five – Evaluation Weights

Not all objectives carry the same importance to the decision maker; therefore, the relative importance of each objective is determined by assigning weights. Determining the weights is somewhat subjective (Kirkwood, 1997), with weights being assigned either locally or globally as shown in Figure 2-5. Using local weighting, the weights on each tier sum to one. Global weights are simply the product of the local weights for all the members of the branch above a given value.

One technique for eliciting local weights from a decision maker is called “swing weighting.” Using this technique, the decision-maker considers the objectives in the same tier of a given branch and ranks them from least to most important. The least important objective is given a weight of *x* and the remaining objectives are scaled as a multiple of *x*. The sum of these weights is set equal to one and the equation is solved to determine the weights of each objective. This process is repeated for each tier in every branch until all the objectives have a weight. Another method is direct assignment, which works well for decision-makers that have a good feel for numbers. Another method assigns weights by divvying up poker chips or marbles. This is sometimes called the 100-marble weighting system (Duncan, 2004). The advantage of either the poker chip or 100-marble methods is that the decision-maker has a visual understanding of the apportioned weights.

Once the decision-maker has assigned local weights, a decision analyst will usually convert these into global weights. This makes it easier to compare the relative importance of all the measures and can be used to help identify better alternatives. For example, suppose the status quo alternative for a particular problem has a disappointing

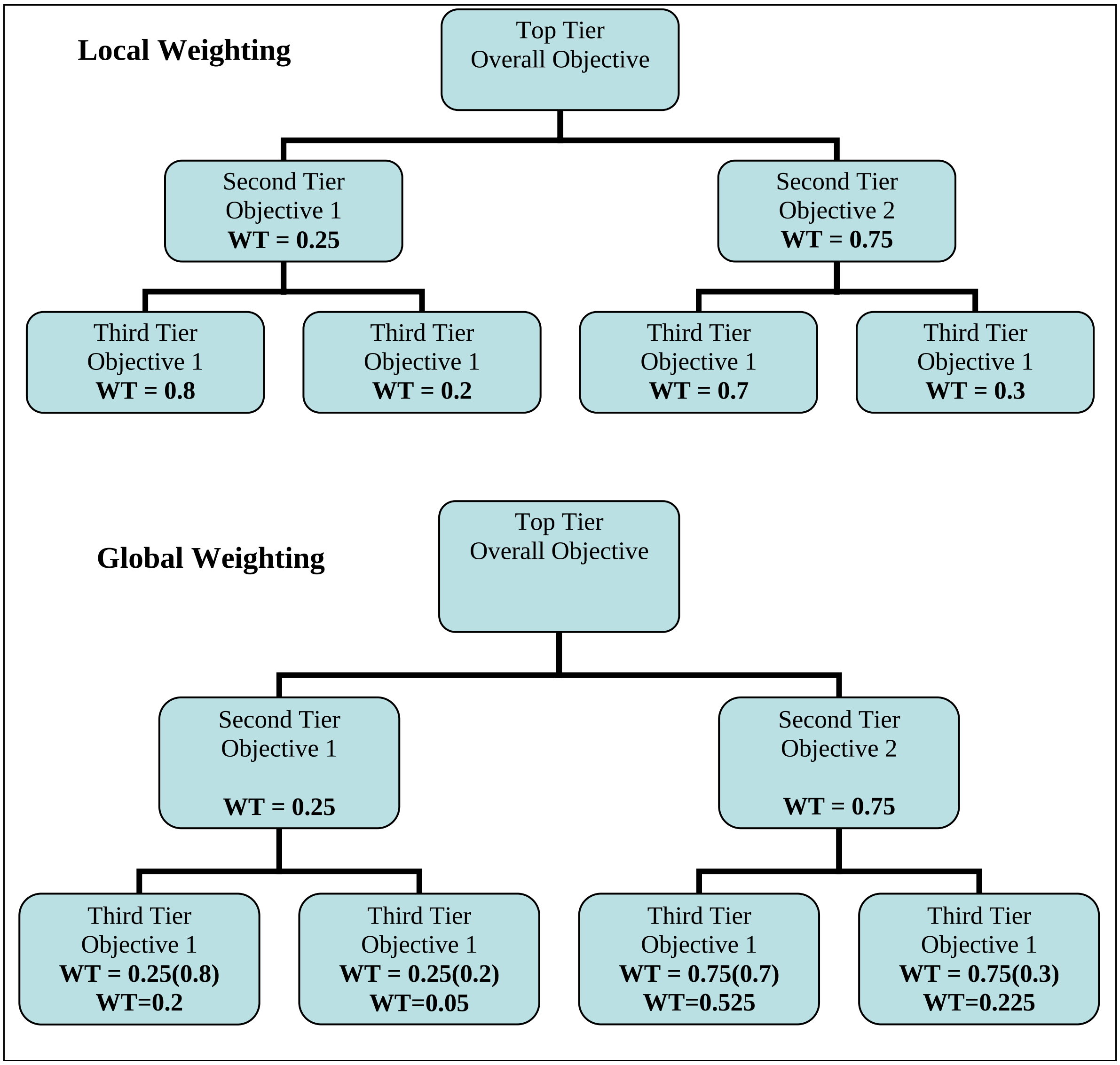

Figure 2-5. Local and Global Weighting (Staats, 2005)

score on those objectives that are most important to the decision-maker. To develop a list of better alternatives to consider, a logical place to start would be to sort the measures by their global weights and consider the few measures that encompass most of the weight. Those measures would point to the neighborhood where the better alternatives might be found. The rest of the measures, those with lower weights, would serve to distinguish the small differences among the better alternatives (Weir, 2005).

2.6.6 Step Six – Alternative Generation

Once the hierarchy has been developed and the weights have been assigned, there are several ways to develop alternatives. The model makes it easy to efficiently evaluate many more alternatives than would be possible otherwise. Team members are often able to suggest alternatives based on previous experiences by a process Kirkwood (1997) calls "associative reasoning." However, there are two primary problems with this method. Even though the experience pool of the team may be extensive, it is not exhaustive. Therefore, the alternatives generated by this method are likely to be the same alternatives that would have been generated by the alternative-focused thinking approach with all of its limitations described earlier. Additionally, relying on previous experience for alternatives rules out innovation and the exploitation of new technologies.

Another way to generate alternatives is by using a strategy table (Kirkwood, 1997). Strategy tables decompose the alternatives into aspects which can be assembled any number of ways. For example, delivering water has aspects of source, treatment, delivery, manning, and packaging as shown in Table 2-16. By combining one block from each of the columns in the table, it is possible to generate a large number of alternatives.

Table 2-16. Strategy-Generation Table for Field Water

Source	Treatment	Delivery	Manning	Packaging
Ground water	None	Contract or Truck	Military	Bottles
Surface water	Conventional filtration		TCN*	Bags
		Military Truck	Ally	Canteen
Municipal system	ROWPU	Pipeline	American Contractor	Water Buffalo
Status Quo	Ultrafiltration	User provided		

* TCN stands for Third Country National.

Exploiting the advantages of a decision model, value gap analysis examines the scores of the better-scoring alternatives and determines if there is a way to modify that alternative in a way to improve the score. For example, if scoring the status quo alternative depicted in Table 2-16 shows a significant loss in value because the bottles are delivered by contractor trucks, it would be simple to tweak the alternative by seeing how it scores if military trucks are used instead.

2.6.7 Step Seven – Alternative Scoring

Once a set of alternatives have been identified, the value hierarchy model is used to score them. This step can be fairly simple if the model is not excessively large and has

measures for which data is readily obtainable. If the measures are too difficult to obtain, the model is too large, or double counting is evident, it may be necessary to reformulate the model.

Even when the model is non-redundant, simply obtaining data can be difficult. For example, what is the true cost of delivering a bottle of water to an Airman in Afghanistan? Is it simply the purchase price? Does one consider the cost of the security forces that inspected the vehicle before it entered the gate? What if military transportation is involved? Does one include the cost of operating the aircraft which protect the convoys on the highway? The problem of obtaining true costs can be a significant challenge and is left to the cost accounting experts because it is beyond the scope of this research effort.

Duncan (2004) provides three simple rules for scoring. First, document the sources of scoring data so the scoring can be repeated or tested. Second, be cognizant of how the measure affects the "value" units earned. Finally, score one measure at a time across all the alternatives to eliminate bias. This way the evaluation of each measure is more likely to be consistent.

2.6.8 Step Eight – Deterministic Analysis

At this point, the data collected from steps 4 (value functions), 5 (weights), and 7 (alternative scores) are combined using an overall value function to determine a rank order of the alternatives. The results should not only indicate the rank order but the degree to which each alternative satisfied the stated objectives of the decision-maker (Weir, 2005). Overall value functions come in many types; however, the additive value

function is most appealing because it is much simpler, the basis is easily understood, and it allows for extensive sensitivity analysis (Stewart, 1995). In order to use an additive value function, the model must be preferentially independent (i.e., the decision-maker's preferences for any objective are independent of the scores of any other objective). If it is not possible to form a satisfactory model with preferential independence, it may be necessary to use a multiplicative value function or some other advanced technique.

If all the conditions necessary for using an additive value function are met the formula is expressed as

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i) \tag{2.1}$$

where $v(x)$ is the overall value (aggregate score) of alternative x, λ_i is the global weight of measure i and $v_i(x_i)$ is the evaluated SDVF for measure i. The astute reader will recognize that this formula calculates the weighted average of the value functions (Kirkwood, 1997).

2.6.9 Step Nine – Conduct Sensitivity Analysis

As mentioned in the previous section, one desirable property of the additive value function is the ability to perform extensive sensitivity analysis. Sensitivity analysis provides an easy and intuitive way to judge whether a particular decision is a good one even if the underlying inputs (e.g., weights or cost) are uncertain. For example, weights assigned directly are often approximate. A decision-maker may want to know if the rank order of the alternatives changes much if the weights vary slightly. With spreadsheets or commercial decision analysis tools, the calculations are easy to perform. If the sensitivity

analysis involves weights, all that is needed is to vary one of the weights and let the other weights change proportionately with the sum of weights equaling one. For an example of how to calculate proportional change, consider a decision involving only three weights. Allowing the weight of the first objective to vary from 0 to 1 requires two equations to calculate the proportional weight of the other two objectives as follows:

$$\lambda_2 = (1 - \lambda_1)\left(\frac{\lambda_2^o}{\lambda_2^o + \lambda_3^o}\right) \tag{2.2}$$

$$\lambda_3 = (1 - \lambda_1)\left(\frac{\lambda_3^o}{\lambda_3^o + \lambda_2^o}\right) \tag{2.3}$$

where λ_2 is the weight of objective 2, λ_3 is the weight of objective 3, λ_1 is the weight of objective 1 (which varies) and λ_2^o and λ_3^o are the initial weights for objective 2 and 3, respectively. Often a sensitivity analysis may indicate the need for additional research or to remove non-sensitive values from the model (Duncan, 2004).

Sensitivity analysis answers the question of whether a small change in the weights, for example, will change the order of the alternatives for the present moment in time. However, the same graphs can be used to see how the order might change if weights change in the future. Forecasting, or risk management given an uncertain future, becomes an additional benefit of the same technique and will be discussed when sensitivity analysis is applied in Chapter 4.

2.6.10 Step 10 – Presentation of Results

The final step is the presentation of results. The goal is to present both results and insights tailored to the question proposed in a manner which is clear and understandable to the decision-maker. A plethora of analysis can be presented, but a thoughtful analyst will include only those analyses that illuminate the advantages and disadvantages of the various alternatives and the circumstances that favor one over another, always keeping in mind that VFT is only a tool. It is useful for providing insight and clarity to a problem, but it does not replace the decision-maker.

Chapter 3. Methodology

Value focused thinking (VFT) was selected as the appropriate decision analysis methodology because the subject problem involves multiple objectives and tradeoffs. Additionally, the solution implementation requires cooperation among multiple organizations. This chapter covers the first six steps of the ten-step VFT process described in Chapter 2. Throughout this process, proxy decision-makers were used. These proxies were chosen to have the perspective of an expeditionary base commander, which meant they were pilots and not civil engineers, logisticians, or medical officers. Each was given "command" of a notional base (Alphastan, Bravostan, and Charliestan) each with its own scenario. Then the decision-makers were familiarized with the problem of field water selection and introduced to the VFT methodology. Acting as expeditionary commanders, they asked questions, decided what was relevant to the scenario, and determined how much importance to give to various considerations.

3.1 Step One – Problem Identification

The Air Force Institute for Operational Health (AFIOH) promotes the readiness and health of the Air Force community. They consult with bases around the world to provide, among other things, water vulnerability assessments. From this perspective, they are concerned about the current practice of using bottled water for field potable water support because it seems to put convenience and morale ahead of water security. Therefore, the fundamental objective for this research was to develop a method which

can effectively and efficiently quantify and illuminate the tradeoffs (e.g., aesthetics versus security) so that better decisions can be made in the field.

To support this research, AFIOH provided three notional bases, which were called Alphastan, Bravostan, and Charliestan. Each provides a realistic and unique situation for which the model can be implemented and tested. Actual bases were not used in this research because such an analysis, including specific vulnerabilities of real bases, would require extra measures to protect classified security information. Besides, it is not necessary to use real data to demonstrate the model's utility.

3.2 Step Two – Create Value Hierarchy

Two ways to develop a value hierarchy are the top-down and bottom-up approaches; this research uses a combination of both. The primary advantage of the top-down approach is that it is better suited to decisions where the alternatives are not well defined at the start (Kirkwood, 1997). The bottom-up approach is used to consider the shortcomings of historical alternatives and to design the hierarchy with objectives and measures that take these shortcomings into account.

The objectives were defined by Air Force policies amended to include the subject matter experts' opinions. Decision analysts refer to this approach, combining insights from stakeholders and policy, as the platinum standard (Staats, 2005). The applicable Air Force policy comes from the *Food and Water Protection Program* (AFI 10-246, 2004) which requires the Base Civil Engineer to develop and maintain an adequate and reliable supply of safe drinking water. The subject matter experts amended these objectives (safety, reliability, and adequacy) with two practical suggestions. First, they

recommended that manpower and cost limitations be included as a factor. Second, they noted the importance of adequately aesthetic and convenient water availability. Regardless of the safety of the water, if it is not aesthetically pleasing and readily available, the reluctance of personnel to consume sufficient quantities of water will result in suboptimal operational health. The resulting first-tier fundamental objectives are shown in Figure 3-1 and will be discussed with their respective second-tier "means" objectives in the following sections.

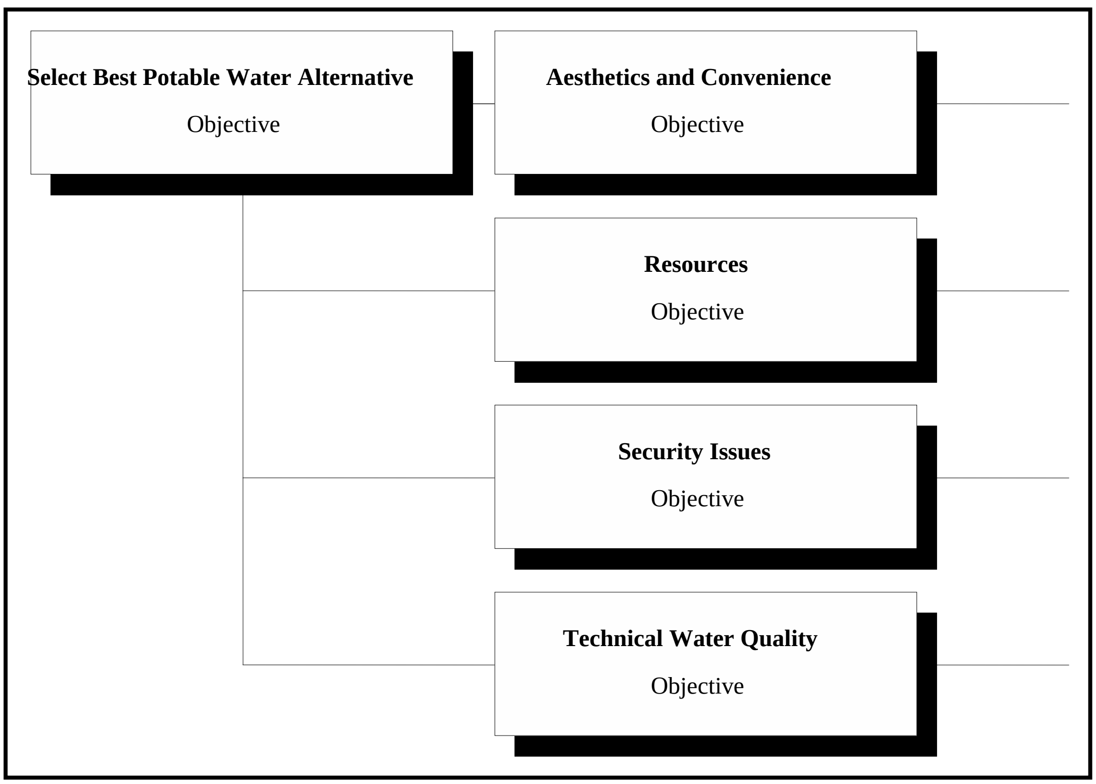

Figure 3-1. First Tier of the Value Hierarchy

3.2.1 Aesthetics and Convenience

The fundamental objective of *Aesthetics and Convenience* is a practical concern encompassing morale and consumer acceptance which results in ensuring operational health. If troops do not drink the water because of how it tastes or looks, they may suffer the effects of dehydration or drink water from unapproved sources. Therefore, aesthetically pleasing water is both a health and a morale issue. On the other hand, a particular commander may decide that hydration is primarily a leadership issue and direct that airmen drink sufficient quantities of the safe water or face disciplinary action. The model can match the commander's preferences simply by adjusting the weights associated with this fundamental objective.

The means objectives for *Aesthetics and Convenience* include the type and size of package and the taste/odor and color of the water itself; these are referred to as *Package* and *Aesthetics* for the second-tier objectives. Airmen probably prefer water from an aesthetically pleasing, appropriately sized bottle. As with all objectives the commander can decide how much weight to give this consumer acceptance/morale aspects.

3.2.2 Resources

The fundamental objective *Resources* refers to working within the limits of *Cost*, *Manpower,* and *Transportation*. These are the typical constraints every organization or operation faces to one degree or another. *Cost* and *Transportation* cover the logistical issues, both of which can be major challenges depending on how water is provided. Revised models are likely to expand the number of resources to account for more complex alternatives.

3.2.3 Security Issues

Security speaks to both the *Safety* and *Reliability* of the potable water supply as identified in AFI 10-246. Security is independent of aesthetics and technical water quality, but is clearly linked to resources. However, security is preferentially independent from resources because the preference for a safe and reliable water supply does not change even if the availability of resources changes. In dire situations when resources are severely limited, a decision-maker may accept a less secure water supply; however, the decision-maker would always prefer a more secure water supply to a less secure one in all situations. *Safety* is used to mean the degree to which the water is either inaccessible to saboteurs or the degree to which an act of sabotage is readily detectible. *Reliability* depends on the degree of redundancy and the amount of stockpile.

3.2.4 Technical Water Quality

Technical water quality refers to the normal absence of harmful substances in the water. This objective comes directly from Air Force doctrine, specifically AFI 10-246, when it calls for water to be “safe.” Technical water quality is distinct and independent from aesthetics, because water with a tinge of color or an off taste can still be safe to drink. Conversely, since some poisons may impart no taste or color, water may be pleasing to the eye and palate but nonetheless lethal.

3.2.5 Summary of Objectives

Before discussing the evaluation measures, it is important to observe that the fundamental and means objectives shown in Figure 3-2 are the same for all locations. However, locations have the capability to vary the weights assigned to each objective. In fact, some locations may give a zero weight to one or more of these fundamental objectives. The ability to tailor the model for a specific location and decision-maker lies in the weighting, which will be discussed in section 3.5. Furthermore, the fundamental and means objectives arranged as they are form a "qualitative value hierarchy" (Jeoun, 2005) which is useful as a guide to information collection, identification of alternatives, and to facilitate communication (Kirkwood, 1995). In order to make this qualitative tool, quantitative evaluation measures must be developed.

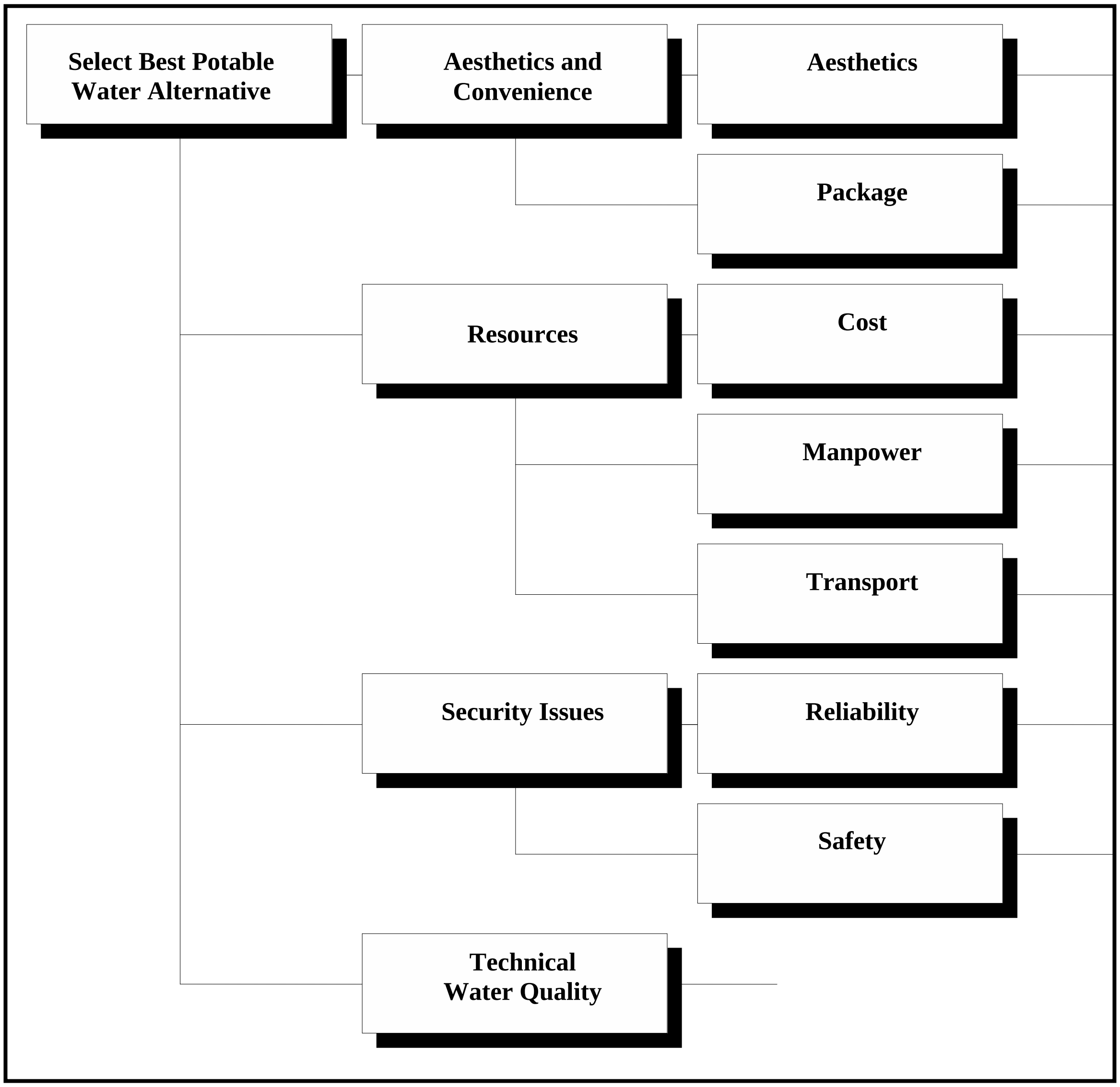

Figure 3-2. Qualitative Value Hierarchy (Jeoun, 2005)

3.3 Step Three – Develop Evaluation Measures

With the value hierarchy developed, the next step involves developing the evaluation measures for the terminal objectives. Evaluation measures turn the value hierarchy, which is a qualitative tool, into a powerful quantitative tool, or model. These measures were either natural or constructed, with either direct or proxy scales. The type of measure and scale were based on the desire to make the model easier to understand and explain. In some cases, potential redundancies were avoided by carefully defining the measures. Table 3-1 provides an overview of the 17 measures developed for this research, with the definitions for each measure included as Appendix B.

Table 3-1. Evaluation Measures of the Value Model

Means Objective	Measure	Scale Type	Measure Unit	Upper Bound	Lower Bound
Aesthetics					
	Color	Constructed Direct	Categorical	Excellent	Colored
	Taste/Odor	Constructed Direct	Categorical	Excellent	Foul
	Temperature	Constructed Direct	Categorical	Cold	Hot
Package					
	Size	Constructed Direct	Categorical	Quart	Five-Gallon
	Type	Constructed Direct	Categorical	Bottle	Bladder
Cost					
	Infrastructure	Natural Direct	Dollars	Site Dependent	Zero
	O&M	Natural Direct	Dollars	Site Dependent	Zero
	Waste Collection	Natural Direct	Dollars	Site Dependent	Zero
Manpower					
	Airmen	Natural Direct	Persons	Site Dependent	Site Dependent
	Contractors	Natural Direct	Persons	Site Dependent	Site Dependent
Transport					
	Aircraft	Natural Direct	Aircraft per week	Site Dependent	Site Dependent
	Trucks	Natural Direct	Trucks per week	Site Dependent	Site Dependent
Reliability					
	Redundancy	Natural Direct	Degrees	Double	Zero
	Stockpile	Natural Direct	Weeks	Ten	Zero
Safety					
	Accessibility	Constructed Proxy	Categorical	Low	High
	Detectability	Constructed Proxy	Categorical	High	Low
Technical Water Quality					
	Water Quality	Constructed Proxy	Categorical	Surpasses EPA Standards	Meets Short Term Standards

Some of the measures such as *Aircraft, Airmen, Trucks*, and *Contractors* are natural measures which are easily understood. Notice these have site dependent bounds. This accounts for the varying requirements and capabilities that are associated with different locations. For example, a site that has few convoy attacks may be willing to use trucks more than a site with frequent convoy attacks. The constructed measures (e.g., C*olor*, *Taste/Odor*, *Temperature, Size, Type*, *Accessibility, Detectability, and Water Quality)* were designed to simplify the assessment. For example, *Color* can be measured objectively using sophisticated analytical equipment (colorimetry). However, since only what the eye can discern affects aesthetics, this research chose to define categories which any person can determine with the naked eye. *Taste/odor* has been defined in much the same way. *Temperature* could have been measured on a continuous scale, but a categorical scale (i.e., hot, warm, cold) was chosen for simplicity and because finer definition is not necessary. *Size* (of the package) addresses convenience and uses a categorical scale to meet the technical requirement for monotonically increasing/decreasing scales for the same reason. *Type* must also be categorical. *Accessibility* refers to the degree to which the water is accessible to a saboteur, and *Detectability* refers to the ability of Airmen to detect intrusion or contamination. Both measures were assessed using a simple categorical scale. *Water Quality* is carefully defined to avoid overlap with *Detectability* and *Aesthetics*. It refers to the absence of harmful substances in the water when the system is operating normally. For example, the municipal water of Kuwait City may have superior water quality (i.e., meets all of the EPA's MCLs) under normal circumstances; but the lack of backflow prevention may, from time to time, allow chemical waste or sewage to contaminate the water system.

This model would handle an alternative to use the Kuwait municipal water by scoring the Water Quality as high but *Detectability* as low unless a sure means of detecting and responding to backflow upsets in a timely fashion could be implemented.

3.4 Step Four – Create Single Dimension Value Functions

The evaluation measures developed in step 3 consist of different measurement units and different scales. Therefore, value functions were developed to convert the units of each measure into unitless values ranging from 0 to 1. Once this conversion has occurred, the value units for each individual value measure may be summed into a total score for the alternative. Two types of value functions were used: piecewise linear (discrete) and exponential (continuous).

The piecewise linear functions were used for measures that fell into categories (e.g., *Accessibility*, *Color*, *Detectability*, *Taste/Odor*, *Temperature,* and *Water Quality*) or into discrete increments (e.g., number of *Airlifts*, *Airmen, Contractors,* and *Trucks*). The returns-to-scale is estimated for each discrete portion of the scale. Monotonically decreasing exponential functions were used for the cost measures (*Infrastructure Costs, O&M Costs,* and *Waste Collection Costs*), with zero cost giving a perfect score and the upper bound determined by location. The shape of the curve was determined by the decision maker estimating where the cost returned half the value.

The equation for the monotonically decreasing exponential value function is provided in Eq. 3.1 (Kirkwood, 1997):

$$v(x) = \left\{ \begin{array}{c} \dfrac{1-\exp[-(High-x)/\rho]}{1-\exp[-(High-Low)/\rho]} \\ \dfrac{High-x}{High-Low} \end{array} \right\} \tag{3.1}$$

where *v(x)* is the exponential value function, *High* is the upper bound of the evaluation measure, *Low* is the lower bound of the evaluation measure, ρ is the exponential constant of the value function (not equal to infinity) and *exp* = the exponential function (e^x).

3.5 Step Five – Weight Value Hierarchy

Weights allow decision-makers to customize the model for their particular situation and preferences. The three notional bases (Alphastan, Bravostan, and Charliestan) were used to establish different weighting schemes. For all three scenarios, the direct weighting technique discussed in Chapter 2 was used to assign weights to the objectives. These local weights were converted to global weights and are compared in Table 3-2. The same information is presented in Table 3-3, except that the measures are shown in rank order according to their weights; the cumulative weights are also shown

Table 3-2. Global Weights for Three Notional Bases

Measure	Alphastan	Bravostan	Charliestan
Accessibility	13.5%	11.3%	2.8%
Airlift	5.8%	6.6%	9.6%
Airmen	3.8%	7.9%	1.8%
Color	0.9%	4.5%	1.5%
Contractors	1.0%	5.3%	3.0%
Detectability	4.5%	3.8%	4.2%
Infrastructure	2.4%	4.4%	8.0%
O&M	2.4%	2.2%	4.8%
Redundancy	6.0%	3.8%	9.1%
Size	0.3%	1.9%	3.0%
Stockpile	6.0%	11.3%	3.9%
Taste/Odor	7.2%	4.5%	2.5%
Temperature	0.9%	2.3%	1.0%
Trucks	1.4%	6.6%	9.6%
Type	0.7%	1.9%	2.0%
Waste Collection	3.2%	2.2%	3.2%
Water Quality	40.0%	20.0%	30.0%
TOTAL	100.0%	100.0%	100.0%

Table 3-3. Rank Order Analysis of Weights for Each Scenario

	Alphastan			Bravostan			Charliestan		
Rank Order	**Measure**	**Wt**	**Cum. Wt.**	**Measure**	**Wt**	**Cum. Wt.**	**Measure**	**Wt**	**Cum. Wt.**
1	Water Quality	0.400	40%	Water Quality	0.200	20%	Water Quality	0.300	30%
2	Accessibility	0.135	54%	Accessibility	0.113	31%	Airlift	0.096	40%
3	Taste/Odor	0.072	61%	Stockpile	0.113	43%	Trucks	0.096	49%
4	Redundancy	0.060	67%	Airmen	0.079	50%	Redundancy	0.091	58%
5	Stockpile	0.060	73%	Airlift	0.066	57%	Infrastructure	0.080	66%
6	Airlift	0.058	79%	Trucks	0.066	64%	O&M	0.048	71%
7	Detectability	0.045	83%	Contractors	0.053	69%	Detectability	0.042	75%
8	Airmen	0.038	87%	Color	0.045	73%	Stockpile	0.039	79%
9	Waste Collect’	0.032	90%	Taste/Odor	0.045	78%	Waste Collection	0.032	82%
10	Infrastructure	0.024	92%	Infrastructure	0.044	82%	Size	0.030	85%
11	O&M	0.024	95%	Detectability	0.038	86%	Contractors	0.030	88%
12	Trucks	0.014	96%	Redundancy	0.038	90%	Accessibility	0.028	91%
13	Contractors	0.010	97%	Temperature	0.023	92%	Taste/Odor	0.025	94%
14	Color	0.009	98%	O&M	0.022	94%	Type	0.020	96%
15	Temperature	0.009	99%	Waste Collection	0.022	96%	Airmen	0.018	98%
16	Type	0.007	100%	Size	0.019	98%	Color	0.015	99%
17	Size	0.003	100%	Type	0.019	100%	Temperature	0.010	100%

Note that the differences in the weights reflect differences in the scenario and differences in the decision makers. For example, Bravostan placed more emphasis on stockpile because it was furthest from the nearest Army camp. Charliestan placed more emphasis on the cost of *Operations* and *Maintenance* because it expected a longer minimum operations timeframe.

3.6 Step Six – Alternative Generation

Alternatives were initially generated by considering the do-nothing alternative (status-quo), the prescribed options and the alternatives suggested by the weights given each measure. For each location, the do-nothing alternative was to continue to provide bottled water from approved sources within the region and delivered by contractor's truck. The prescribed options were to tap into the water systems of local municipalities, if considered economical, and force protection is good, or to drill a minimum of two wells (CENTCOM, 2002).

3.6.1 Alternatives for Alphastan

A list of alternatives for Alphastan includes the do-nothing and prescribed alternatives, as well as alternatives based on the first five measures in Table 3-3. These measures represent 73 percent of the cumulative weight and consist of *Water Quality, Accessibility, Taste/odor, Redundancy,* and *Stockpile.* Two alternatives will be generated by consideration of the weights. After discussing the options suggested by these weights, Table 3-4 lists the alternatives considered for Alphastan.

For the first new alternative, consider the most highly weighted measure: *Water quality*. The best water quality can be expected from treated well water or water that is from a municipal system. Additionally, *Accessibility* strongly favors well water over municipal water and bottled water. Therefore, the best alternative should have well water that is treated by ROWPU. Now consider the third most important measure: *Taste/Odor.* ROWPU scores poorly for *Taste/Odor* if it is stored in the normal rubber bladders. Suppose fiberglass storage tanks, shaded from the sun, to reduce the necessity of higher

chlorine additions replaces the rubber bladders. Finally, use two wells and two ROWPU units to increase the redundancy score and use enough fiberglass storage tanks to maximize the stockpile score. The resulting alternative (A4) may score well.

For the second new alternative, suppose one considers a surface source. Surface water can be filtered by ROWPU to achieve the highest score for *Water Quality*. However, water from a ditch is highly accessible to sabotage. One way to essentially reduce this *Accessibility* is to build a reservoir of sufficient size inside the base perimeter where it can be guarded. This would also improve the *Detectability* because a saboteur would need a truck to contaminate a large reservoir and detection of a truck is easier than detection of a person on foot. The resulting alternative (A5) may score reasonably well, if the improvements to *Water Quality* and *Accessibility* outweigh the *Taste/Odor* penalty.

Table 3-4. Initial Alternatives for Alphastan

#	Description	Source
A1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume three suppliers (double-redundancy)	Do nothing, or status quo, alternative
A2	Drill at least two wells. Filtration by ROWPU, store, and distribute water using the normal ROWPU vinyl/rubber/canvas sacks/bladders.	Prescribed alternatives
A3	Tap into local water system. No special filtration.	
A4	Same as (A2), but store water in multiple and separated fiberglass tanks out of direct sunlight to increase stockpile and reduce the dosage of chlorine necessary to maintain a residual.	Alternatives suggested by weights
A5	Build reservoir for raw surface water to reduce accessibility, filter using ROWPU.	

3.6.2 Alternatives for Bravostan

A list of alternatives for Bravostan includes the first three Alphastan alternatives, i.e., the do-nothing and prescribed options. Additional alternatives were developed by considering the first eight measures in Table 3-3. These measures represent 73 percent of the cumulative weight and consist of *Water Quality*, *Accessibility, Stockpile, Airmen, Airlift, Trucks, Contractors,* and *Color*. This is more measures than Alphastan but still considerably simpler than looking at all 17 measures. Two alternatives will be generated by consideration of the weights. After discussing the options suggested by these weights, Table 3-5 lists the alternatives considered for Bravostan.

For the first new alternative, consider that the importance of *Taste/Odor* is significantly reduced relative to Alphastan. This suggests not pursuing fiberglass tanks. Next, consider that the top four measures are *Water Quality*, *Accessibility, Stockpile,* and *Airmen.* Alternative B2 should score well for the first two measures, but a new alternative based on B2 could potentially score even better by increasing the stockpile and substituting contractors for Airmen. This becomes the first new alterative, B4.

For the second new alternative, suppose one considers a surface water source. Construction of a reservoir of sufficient size could improve the scores for *Accessibility.* Then, *s*ubstituting contractors for Airmen should improve the scores as well. This becomes the second new alternative, B5.

Table 3-5. Alternatives for Bravostan

#	Description	Source
B1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)	Do nothing, or status quo, alternative
B2	Drill at least two wells. Filtration by ROWPU, store, and distribute water using the normal ROWPU vinyl/rubber/canvas sacks/bladders.	Prescribed alternatives
B3	Tap into local water system. No special filtration.	
B4	Same as (B2), but store ten weeks of stockpile and provide labor by contractors.	Alternatives suggested by weights
B5	Build reservoir for raw surface water to reduce accessibility, filter by ROWPU, store ten weeks of stockpile and provide labor by contractors	

3.6.3 Alternatives for Charliestan

A list of alternatives for Charliestan begins with the same three alternatives used for Alphastan and Bravostan. Additional alternatives were developed by considering the first seven measures in Table 3-3. These measures represent 75 percent of the cumulative weight and consist of *Water Quality, Airlift, Trucks, Redundancy, Infrastructure, O&M,* and *Detectability*. The decision-maker for Charliestan is less concerned about stockpile and more concerned about minimizing the use of airlift and trucks as well as expenses associated with infrastructure, operations, and maintenance. Two alternatives will be generated by consideration of these seven measures. After describing the rational for each new measure, Table 3-6 lists all the alternatives considered for Charliestan.

For the first new alternative, consider that the top five measures are *Water Quality, Airlift, Trucks, Redundancy*, and *Infrastructure.* Alternative C2 should maximize the first three measures. A new alternative could potentially improve upon C2 if it can have less

infrastructure costs. Therefore, the new alternative C4 is the same as C2 but uses surface water instead of well water. Qualitatively, one can see that this will result in a lower score for the measures of *Accessibility* and *Detectability*.

For the second new alternative, augment C4 by considering the fifth most important measure, *O&M*. Ultrafiltration promises most of the capabilities of ROWPU with much less energy costs because the membranes operate at significantly reduced pressures. Since the source is surface water, which does not contain salt, ultrafiltration is an option to consider. Supposing ultrafiltration is sufficient to produce high quality water, the fifth alterative C5 is the same as C4 but uses ultrafiltration instead of ROWPU.

Table 3-6. Alternatives for Charliestan

#	Description	Source
C1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)	Status-Quo alternative
C2	Drill at least two wells. Filtration by ROWPU, store, and distribute water using the normal ROWPU onion sacks.	Prescribed Alternatives
C3	Tap into local water system. No special filtration.	
C4	Same as (C2) but minimize installation costs by using surface water instead of wells	Alternatives suggested by Weights
C5	Same as (C4) but reduce operations and maintenance costs by using Ultrafiltration instead of ROWPU	

3.6.4 Summary of Alternatives

Table 3-7 was created as a quality check, summary, and an aid to scoring. Each alternative listed across the top of the table is developed by selecting ala carte from identified sources, treatments, storage, and manpower options. In this way, the table is able to summarize the results of multiple strategy tables at a glance. Observe that (A1, B1, C1) are the same as are (A2, B2, C2), and the same as (A3, B3, C3). This is because these alternative sets were the status quo and prescribed options common to all scenarios considered. Alternative sets (A4, B4, C4) and (A5, B5, C5) were designed with the weighting of each scenario in mind, so there are differences between them. Having one table to look at aides in the effort to compile the data necessary for scoring.

Table 3-7. Summary of Alternatives for All Three Locations

	A1	B1	C1	A2	B2	C2	A3	B3	C3	A4	B4	C4	A5	B5	C5
Source															
Bottled Water	X	X	X												
Well Water				X	X	X				X	X				
City Water							X	X	X						
Surface Water												X	X	X	X
Treatment															
ROWPU				X	X	X				X		X	X	X	
CWPU															
Ultrafiltration															X
Conventional Treatment															
None	X	X	X				X	X	X						
Storage															
PET Bottles	X	X	X												
Fiberglass tanks										X					
Vinyl/Rubber tanks				X	X	X	X	X	X		X	X		X	X
Raw Water Reservoir													X	X	X
Manpower															
Airmen	X	X	X	X	X	X	X	X	X			X	X		X
Contractor											X			X	

Chapter 4. Results and Analysis

This chapter covers steps 7 through 9 of the ten-step value focused thinking (VFT) process. Since this research used three notional bases, the results of these steps are presented for each base in sequence. The cost data used in the model comes from various sources, including professional cost estimation (fiberglass tank construction), do-it-yourself cost estimation using readily available references and Air Force escalation tables (well drilling) and rule of thumb estimations (pipeline). The cost of bottled water, which can vary widely from location to location, was selected conservatively for all locations to be 10 cents per liter. Actual bottled water costs from recent history range from 20 cents per liter to as high as $1.50 per liter. Escalation construction cost data from Saudi Arabia was used as a surrogate since real data was not available. The cost data used is approximate but considered adequate for the scope of this research. The specific cost sources are referenced with the respective calculations in Appendix C.

4.1 Alphastan Scenario

Alphastan is situated 25 miles from the nearest developed city, 5 miles from the nearest village, 10 miles from the nearest Army Camp, and 200 miles from a seaport. The base population varies between 1,700 and 2,000, with approximately 1,500 Airmen and the rest Marines. The mission is to provide stability for reconstruction while a transitional government develops its military and police forces to assume the security functions. The threat assessment includes attacks on convoys; there is also non-specific

intelligence suggesting the insurgents seek to target food and water supplies. Central Command (CENTCOM, 2002) recommends that bases stop using bottled water as soon as possible and either connect to the municipal water system, if force protection can be assured, or drill a minimum of two wells. The following sections cover the scoring and analysis of alternatives for Alphastan. Recall that the five alternatives developed for Alphastan were provided in Table 3-4. The measures from Table 3-3 and the respective scores for Alphastan are shown in Table 4-2. Calculations supporting the cost measure are provided in Appendix C. The results of steps 7 through 9 are subsequently discussed in the following sections. Table 4-1 provides the project information necessary to score the alternatives.

Table 4-1. Project Information for Alphastan

Design Parameter	Value
Number of people served Design for	2,000 3,000
Stockpile Goal	10 weeks
Depth to serviceable water	500 feet
Operational life of infrastructure (Worst Case)	1 year
Distance to nearest municipal water supply	25 miles
Cost of Bottled Water Conservative price (real prices often higher)	10 cents per liter

Table 4-2. Measures for Alphastan's Initial Alternatives

Means Objective	Measure	Measure Unit	Upper Bound	Lower Bound	Alternatives				
					A1	A2	A3	A4	A5
Aesthetics									
	Color	Categorical	Excellent	Colored	Excellent	Excellent	Excellent	Excellent	Excellent
	Taste/Odor	Categorical	Excellent	Foul	Excellent	Slight	Excellent	Good	Slight
	Temperature	Categorical	Cold	Hot	Cold	Warm	Warm	Hot	Warm
Package									
	Size	Categorical	1.5 Liter	5 Gal	1.5 L	Liter	Liter	Liter	Liter
	Type	Categorical	PET Bottle	Bladder	PET Bottle	Canteen	Canteen	Canteen	Canteen
Cost									
	Infrastructure	Cents per Liter	200	Zero	1.3	3	0.96	4.62	3.20
	O&M	Cents per Liter	200	Zero	10	0.3	0.1	0.46	1.91
	Waste Collection	Cents per Liter of water provided	10	Zero	1	0.1	0.01	0.01	0.01
Manpower									
	Airmen	People	6	Zero	2	4	1	2	4
	Contractors	People	10	Zero	0	0	0	0	0
Transport									
	Aircraft	Aircraft per week	5	Zero	0	0	0	0	0
	Trucks	Trucks per week	70	Zero	8.6	0.25	0	0.25	0.25
Reliability									
	Redundancy	Categorical	Triple	None	Double	Single	None	Single	Single
	Stockpile	Weeks	20	0	4	4	1	10	10
Safety									
	Accessibility	Categorical	Inside the Fence/Out of Sight/Watched Continuously	Outside the fence, not watched	Outside the fence, not watched	Inside the fence, visible	Outside the fence, not watched	Inside the fence, visible	Inside the fence, visible
	Detectability	Categorical	Very High	Low	Low	Very High	Low	Very High	Medium
Technical Water Quality									
	Water Quality	Categorical	Very High	Low	High	Very High	High	Very High	Very High

4.1.1 Step Seven – Alternative Scoring for Alphastan

The model calculates total value scores using the additive value function described in section 3.4. The results are shown in Figure 4-1, which presents the scores for the five alternatives that were considered initially, before sensitivity analyses suggested new alternatives. The results show that alternatives which rely on drilling wells scored better than the rest. Three alternatives did better than the do-nothing alternative and one suggested by CENTCOM scored at the bottom of the alternatives considered. For Alphastan and the weights elicited from the decision-maker, the best of the evaluated alternatives is to drill two wells, filter the water using ROWPU, and store the water in fiberglass tanks instead of rubber bladders.

Ranking for Select Best Potable Water Alternative Goal

Alternative	Value
A4. Drill Wells, Store Water in Fiberglass Tanks	0.861
A2. Drill Two Wells	0.834
A5. Build raw water reservoir, filter using ROWPU	0.816
A1. Do Nothing	0.721
A3. Tap into local water system	0.705

Figure 4-1. Initial Alternative Scoring for Alphastan

4.1.2 Step Eight – Deterministic Analysis for Alphastan

A deterministic analysis provides the decision-maker with better insight as to why certain alternatives scored well and others scored poorly. For example, Figure 4-2 displays how well each alternative performed for each fundamental objective. The biggest difference between the top three and bottom two alternatives is in the value attributed to the *Security* objective. Specifically, the gains in security more than offset the additional expenses involved for Alphastan. Considering A4 and A2, one can see the improvements in *Aesthetics* were worth the additional cost associated with the fiberglass tanks, which is reflected in the shorter bar for the *Resources* objective.

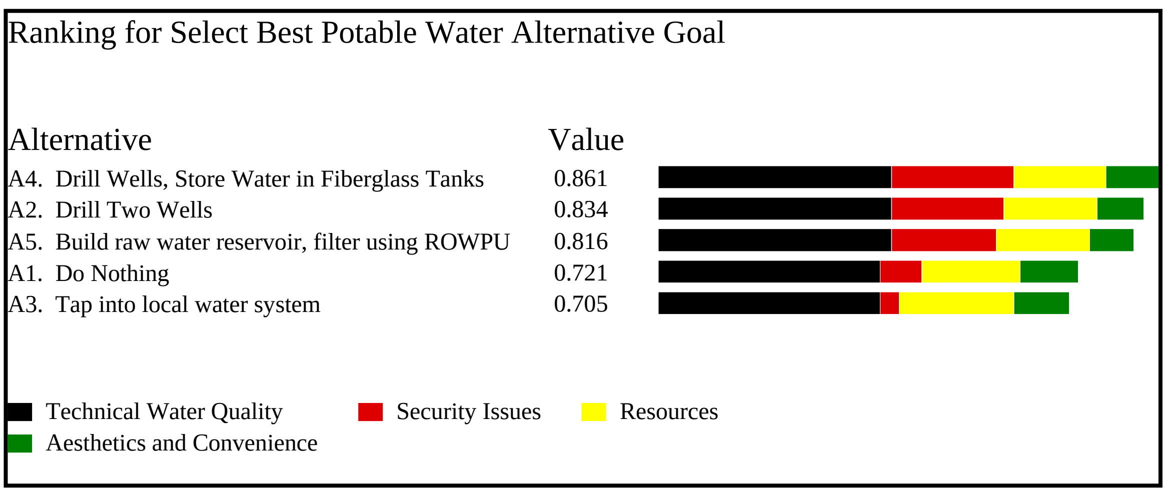

Figure 4-2. Fundamental Objective's Contributions for Alphastan

4.1.3 Step Nine – Sensitivity Analysis for Alphastan

A sensitivity analysis of the fundamental objectives was conducted to see if any of these objectives were sensitive to changes in weighting. A measure is considered sensitive to changes in weighting if the rank ordering of the alternatives changes within a realistic probability of the weights (Jeoun, 2005). The results of this analysis are discussed in the following sections.

4.1.3.1 *Aesthetics and Convenience* Sensitivity Analysis for Alphastan

The results of allowing the weight on the *Aesthetics and Convenience* objective to vary from 0 to 1 are shown in Figure 4-3. The initial weight of 9 percent is shown as the vertical line in the figure. As the chart shows, the top-ranked alternative remained the top choice unless the weight is above 70 percent. This represents an increase of over 800 percent in the weight associated with this objective, which is probably not very realistic. Therefore, the fundamental objective of *Aesthetics and Convenience* is considered insensitive to changes in the weight. Notice, additionally, that two of the slopes are negative and three are positive. The alternatives with negative slopes rely on the rubber bladder storage systems typical of ROWPU operations. In contrast, the one ROWPU alternative that has a positive slope stores water in fiberglass tanks.

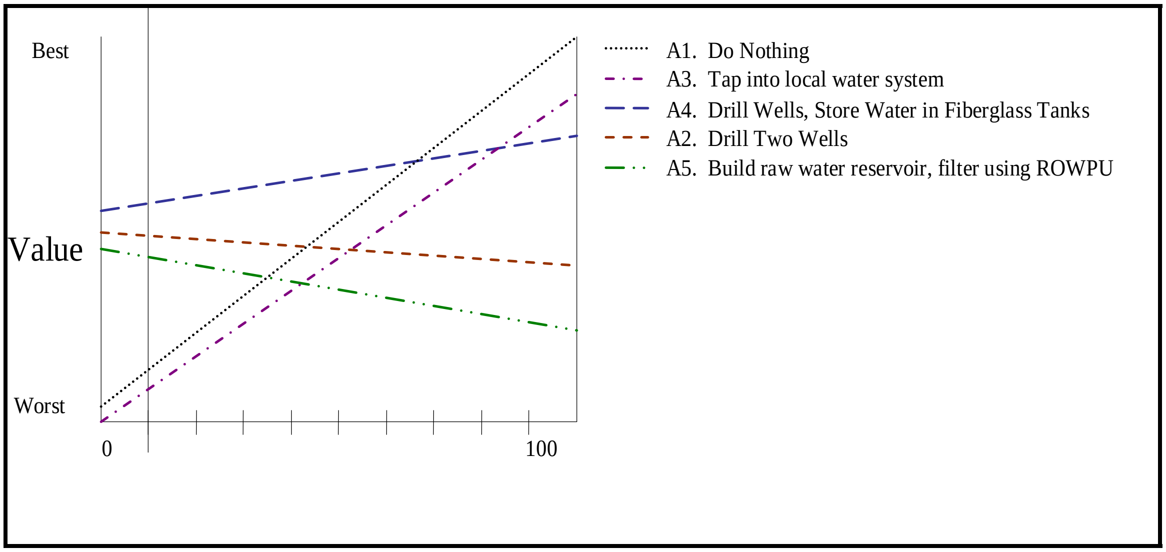

Figure 4-3. Sensitivity Analysis of Aesthetics and Convenience for Alphastan

4.1.3.2 *Resources* Sensitivity Analysis for Alphastan

The best alternative (Drill Two Wells, Store water in Fiberglass Tanks) remained the top choice unless the weight given *Resources* is above 58 percent. Strictly speaking, this measure is insensitive because the decision maker's approximation may be off a little but not so much as to make a difference in the rank order, especially among the top four alternatives shown in Figure 4-4.

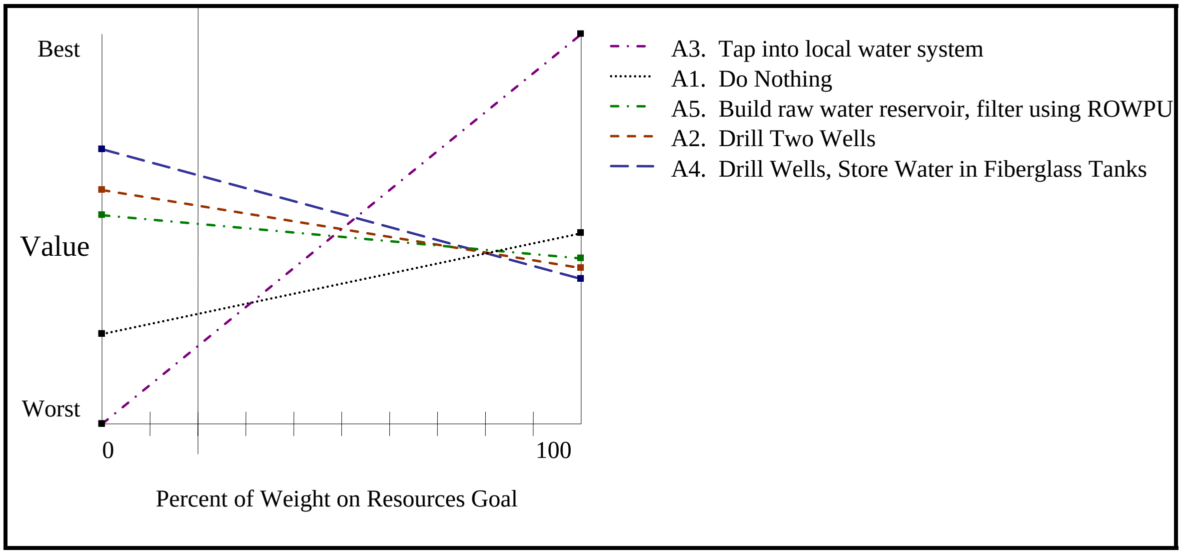

Figure 4-4. Sensitivity Analysis of *Resources* for Alphastan

Using this same figure, one can consider what the impact may be of changes to the importance of resources as the military operation continues into the future. In this light, it seems within reason that the importance of resources could change significantly over time; thus, in a different sense, it is "sensitive" with respect to the *Resources* objective. For the purposes of this research, the term *sensitivity* may be used when discussing risk analysis or forecasting. The reader should keep in mind that sensitivity analysis and forecasting are different. When one considers the possibility of the weight given *Resources* over time (i.e., forecasting), notice that the worst alternative becomes the best alternative—a complete reversal. This sensitivity to the *Resources* weighting suggests further analyses, which are examined in the following paragraphs.

Digging deeper into the reasons behind the ranking reversal, consider the *Cost* objective shown in Figure 4-5, which appears to be somewhat sensitive as well. If the weight on *Cost* goes above 60 percent, the rank order reverses. This proves that part of the sensitivity of *Resources* is, at least partially, due to *Cost*, which may become more of an issue as the political support for or

against military operations changes. Note, however, that the cost considered above includes the installation costs which are high at first and smaller, per unit of water, as the operations continue. If a decision-maker wants to look at which alternatives are favorable in case future support for ongoing costs is reduced, a closer look effect of changing the weight for the *O&M* measure is recommended, which is presented in Figure 4-6.

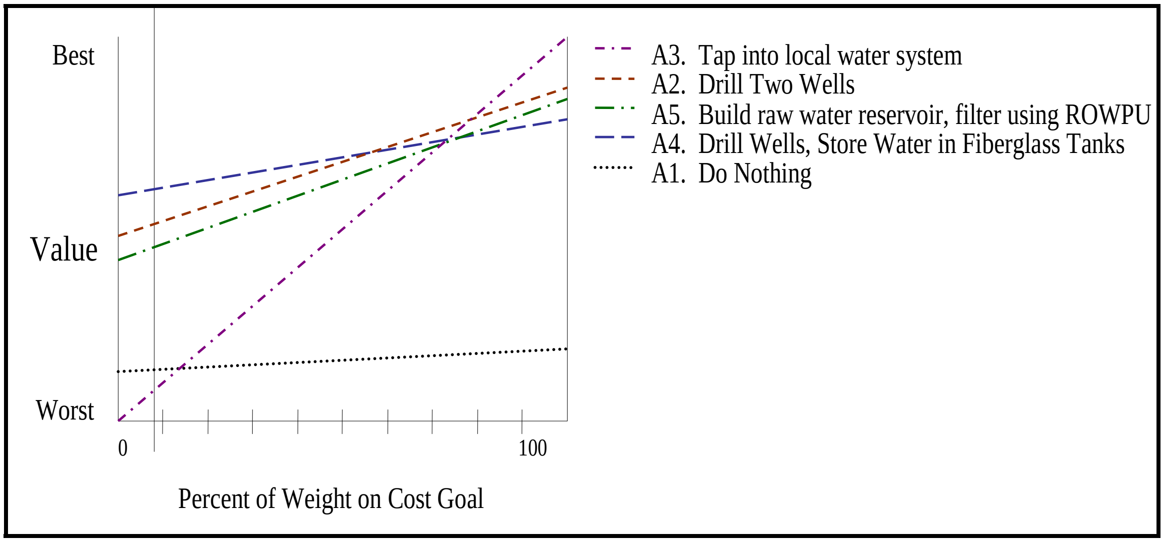

Figure 4-5. Sensitivity Analysis of Cost for Alphastan

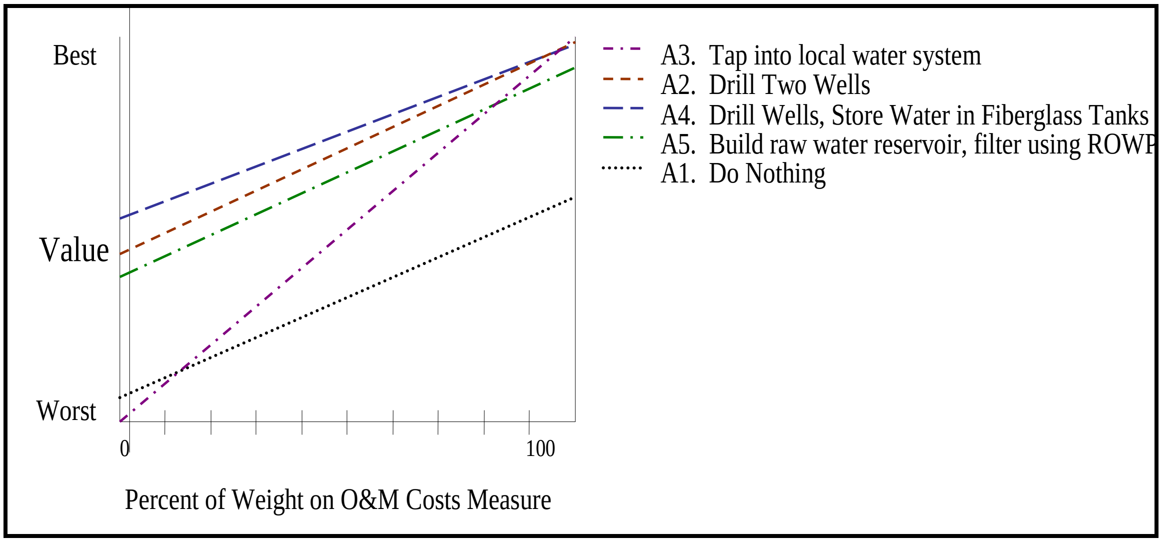

Figure 4-6. Sensitivity Analysis of O&M Costs for Alphastan

As is the case for all of the *Resource* branch sensitivity analyses, the rank order is also sensitive to changes in the *O&M* weighting, but only if one considers the lowest two alternatives. Observe that A4, A2, and A5 are good choices even if constrains in the O&M budget change in the future. Also, notice that A1 scores poorly against all the alternatives considered even if the weight given *O&M Costs* is very small. The reason for this is the susceptibility of A1 to disruption or sabotage.

Consider the sensitivity analysis of the *Manpower* objective shown in Figure 4-7. If the weight for *Manpower* is above 20 percent, the do-nothing alternative, which uses 2 personnel versus 4, becomes the top alternative for a very short range; beyond that, the top alternative changes again to one that requires only 1 person. While the precision with which the decision maker picked the weight may be sufficient to say the rank order is not sensitive, looking at the

same figure suggests a more robust alternative. One option that might be better if manpower becomes more critical in the future, would be to consider using contractors to replace Airmen. Alternative six (A6) thus becomes: Drill two wells, filter the raw water by ROWPU, store the product water in fiberglass tanks and use contract labor instead of Airmen. Scoring this new alternative results in a new top score of 0.893 (Figure 4-8), which dominates the others for nearly the full range of weight given the *Manpower* objective (Figure 4-9).

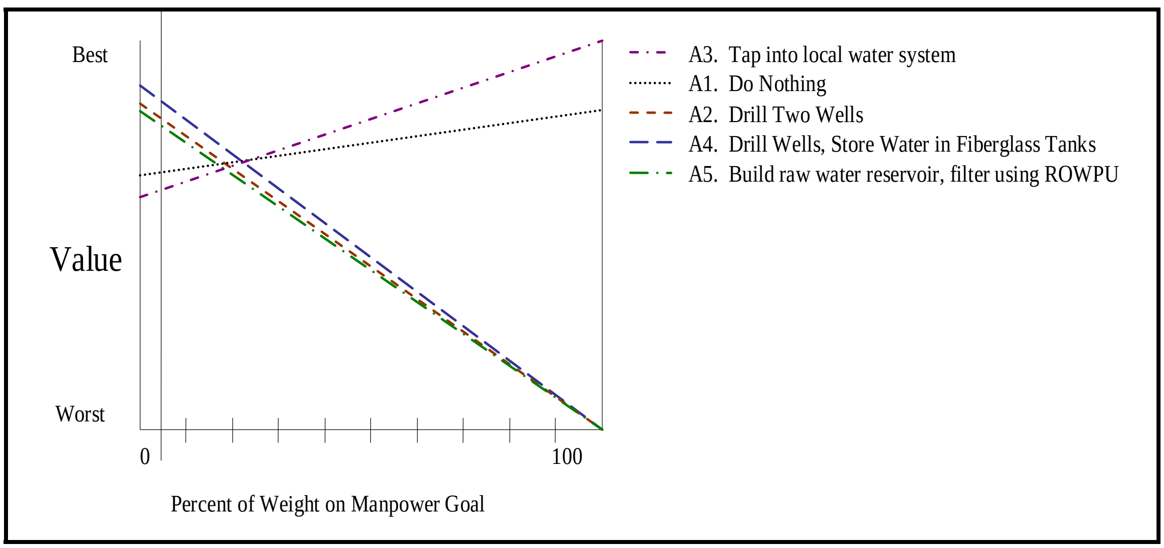

Figure 4-7. Sensitivity Analysis of Manpower for Alphastan

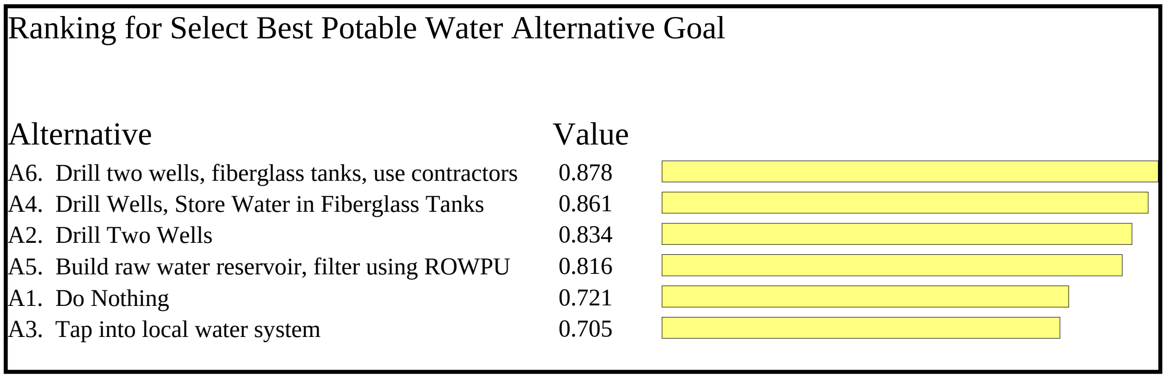

Figure 4-8. Alternative Scoring for Alphastan

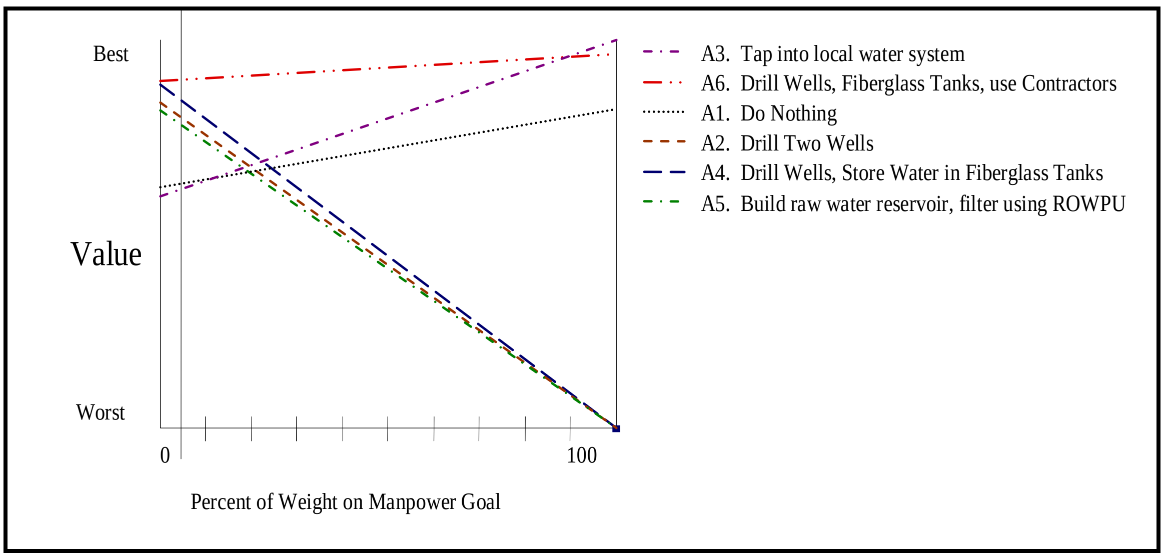

Figure 4-9. Sensitivity Analysis of Manpower, using Contractors for Alphastan

4.1.3.3 *Security* Sensitivity Analysis for Alphastan

The new alternative (Drill Two Wells, Store water in Fiberglass Tanks, and provide labor using Contractors) holds the top rank for the entire range of weights that may be given to *Security*. Note also that the top three alternatives (A6, A4, and A2) also hold their relative positions well for the same range. Therefore, a decision-maker can be sure the top three alternatives (A6, A4, and A2) remain the best for most conceivable changes in the importance of *Security*. This is reflected in Figure 4-10.

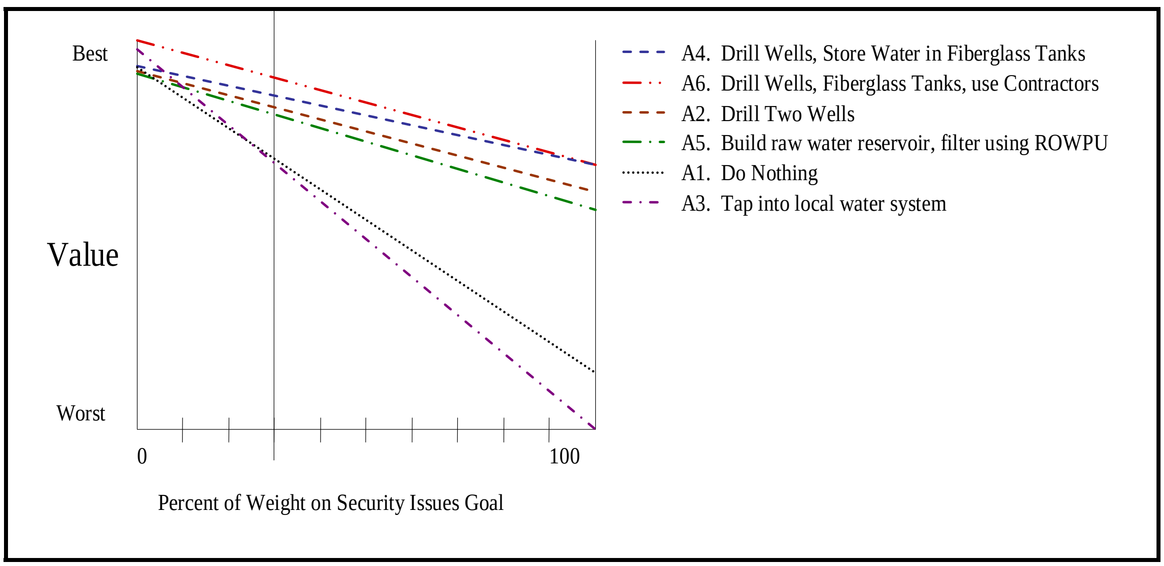

Figure 4-10. Sensitivity Analysis of Security for Alphastan

4.2 Bravostan Scenario

Bravostan is situated 10 miles from the nearest developed city, 5 miles from the nearest village, 100 miles from the nearest Army Camp, and 150 miles from a seaport. The base population varies between 2500 and 3000 with 2000 Airmen and the rest Soldiers. The mission is to provide stability for reconstruction while a transitional government develops its military and police to take over the security functions. The threat assessment includes attacks on convoys and non-specific chatter suggesting insurgents seek to target food and water supplies. Central Command (CENTCOM, 2002) recommends that bases stop using bottled water as soon as possible and either connect to the municipal water system, if force protection can be assured, or drill a minimum of two wells. The following sections cover the scoring and analysis of alternatives for Bravostan. Relevant project information is given in Table 4-3. Table 4-4 lists all of the measures used in the scoring.

Table 4-3. Project Information for Bravostan

Design Parameter	Value
Number of people served Design for	3,000 4,000
Stockpile Goal	10 weeks
Depth to serviceable water	500 feet
Operational life of infrastructure (Worst Case)	1 year
Distance to nearest municipal water supply	10 miles
Cost of Bottled Water Conservative price (real prices often higher)	10 cents per liter

Table 4-4. Measures for the Bravostan Alternatives

Means Objective	Measure	Measure Unit	Upper Bound	Lower Bound	Alternatives				
					B1	B2	B3	B4	B5
Aesthetics									
	Color	Categorical	Excellent	Colored	Excellent	Slight	Excellent	Excellent	Excellent
	Taste/Odor	Categorical	Excellent	Foul	Excellent	Slight	Excellent	Good	Slight
	Temperature	Categorical	Cold	Hot	Cold	Warm	Warm	Hot	Hot
Package									
	Size	Categorical	1.5 Liter	5 Gal	1.5 L	Liter	Liter	Liter	Liter
	Type	Categorical	PET Bottle	Rubber Bladder	PET Bottle	Canteen	Canteen	Canteen	Canteen
Cost									
	Infrastructure	Cents per Liter	200	Zero	1.3	3.5	0.29	3.51	3.59
	O&M	Cents per Liter	200	Zero	10	0.35	0.03	4.80	5.60
	Waste Collection	Cents per Liter of water provided	10	Zero	1	0.01	0.01	0.01	0.01
Manpower									
	Airmen	People	6	Zero	2	4	1	0	0
	Contractors	People	10	Zero	0	0	0	4	4
Transport									
	Aircraft	Aircraft per week	5	Zero	0	0	0	0	0
	Trucks	Trucks per week	70	Zero	13.0	0.25	0	0.25	0.25
Reliability									
	Redundancy	Categorical	Triple	None	Double	Single	None	Single	Single
	Stockpile	Weeks	20	0	4	4	1	10	10
Safety									
	Accessibility	Categorical	Inside the Fence/Out of Sight/Watched Continuously	Outside the fence, not watched	Outside the fence, not watched	Inside the fence, visible	Outside the fence, not watched	Inside the fence, visible	Inside the fence, visible
	Detectability	Categorical	Very High	Low	Low	Very High	Low	Very High	Medium
Technical Water Quality									
	Water Quality	Categorical	Very High	Low	High	Very High	High	Very High	Very High

4.2.1. Step Seven — Alternative Scoring for Bravostan

The model calculates scores the same as was explained in section 4.1.1. using the additive value function. Figure 4-11 presents the scores for the five alternatives evaluated for Bravostan. Here one can see the fourth and fifth alternatives which were designed to score well considering the measures with the highest weights did score well, beating the do-nothing and the alternatives prescribed by CENTCOM (2002).

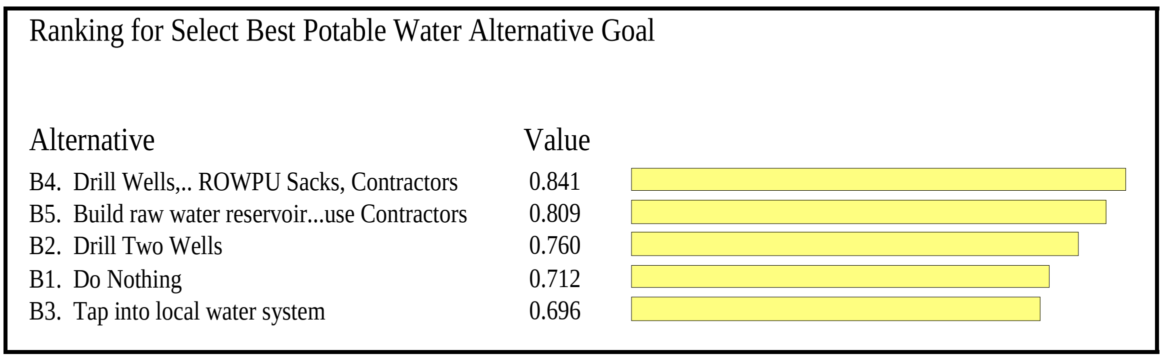

Figure 4-11. Alternative Scoring for Bravostan

4.2.2 Step Eight – Deterministic Analysis for Bravostan

A deterministic analysis provides the decision maker with better insight as to why certain alternatives scored well and others scored poorly. Figure 4-12 displays how well each alternative performed for each fundamental objective. The biggest difference between the top three and the bottom two alternatives, again, is the differences in value scores for the *Security* objective. It is also easy to see that the top two alternatives scored better because they demanded fewer resources than B2, which is because these used contractors for labor. Even though B2 used the fewest resources it did not score well overall because it scored poorly for security issues.

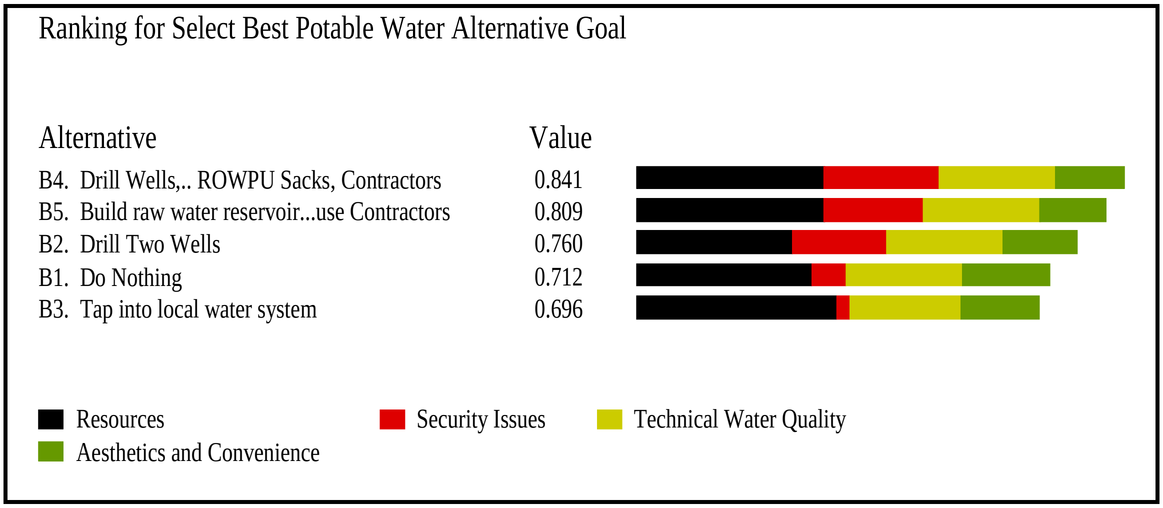

Figure 4-12. Fundamental Objective's Contributions for Bravostan

4.2.3 Step Nine – Sensitivity Analysis for Bravostan

First, a sensitivity of the fundamental objectives was conducted to see if any of these objectives was sensitive to changes in weighting. An objective or measure is sensitive to changes in weighting if the rank ordering of the alternatives changes within a realistic probability of the weights (Jeoun, 2005). The sensitivity/insensitivity will be discussed after each analysis is performed in the following sections.

4.2.3.1 *Aesthetics and Convenience* Sensitivity Analysis of for Bravostan

The sensitivity analysis shown in Figure 4-13 shows the worst place to first place as the weight given *Aesthetics and Convenience* crosses over 50 percent. Even though the change in weights is less than half the span it remains unlikely a decision-maker would give *Aesthetics and Convenience* more than 50 percent of the weight because the

importance to military decision-makers for safety and reliability is too great, normally. Therefore the *Aesthetics and Convenience* objective is considered insensitive.

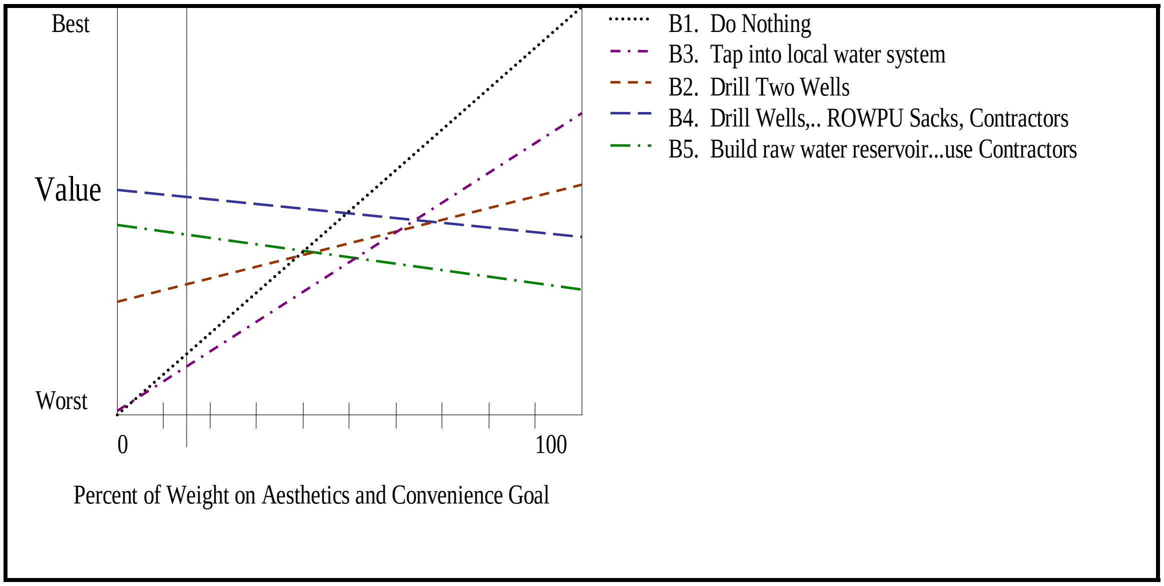

Figure 4-13. Sensitivity Analysis of *Aesthetics and Convenience* for Bravostan

4.2.3.2 *Resources* Sensitivity Analysis for Bravostan

Figure 4-14 shows the best alternative (Drill Two Wells, Store water in ROWPU Sacks) holds the top rank unless the weight given *Resources* is above 80 percent. Although, it seems likely in the course of a military campaign that the weight given resources might increase, such a large swing seems relatively unlikely. Furthermore, the biggest expense of resources for our top alternative is an initial expense and not a continuing expense, so change in the weighting overtime should have no impact on the order. However, if the weight for resources should rise above 80 percent the bottom alternative becomes the top alternative.

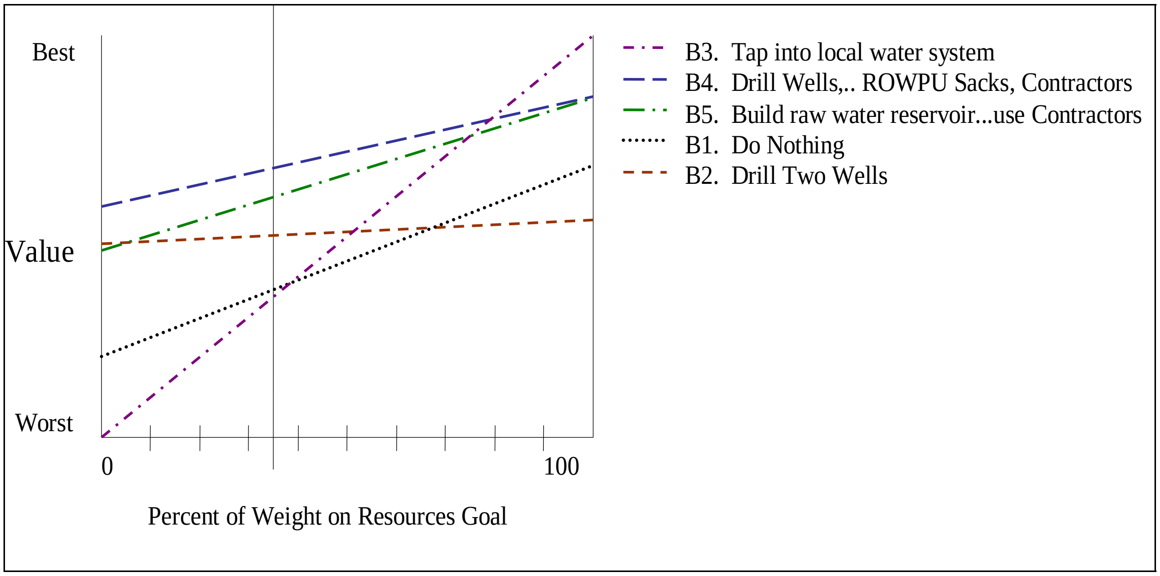

Figure 4-14. Sensitivity Analysis of Resources for Bravostan

4.2.3.3 *Security* Sensitivity Analysis for Bravostan

The top-scoring alternative (Drill Two Wells, Store water in ROWPU Sacks) maintains it's position unless weight given *Security* is below approximately 7 percent. This measure is considered, therefore, insensitive. Forecasting, it seems unlikely in a military operation that the weight given security should change enough to result in a different ranking of the alternatives considered. Therefore a decision-maker can be sure the top three alternatives (B4, B5, and B2) are the best and will remain the best for most conceivable changes in the importance of security (Figure 4-15).

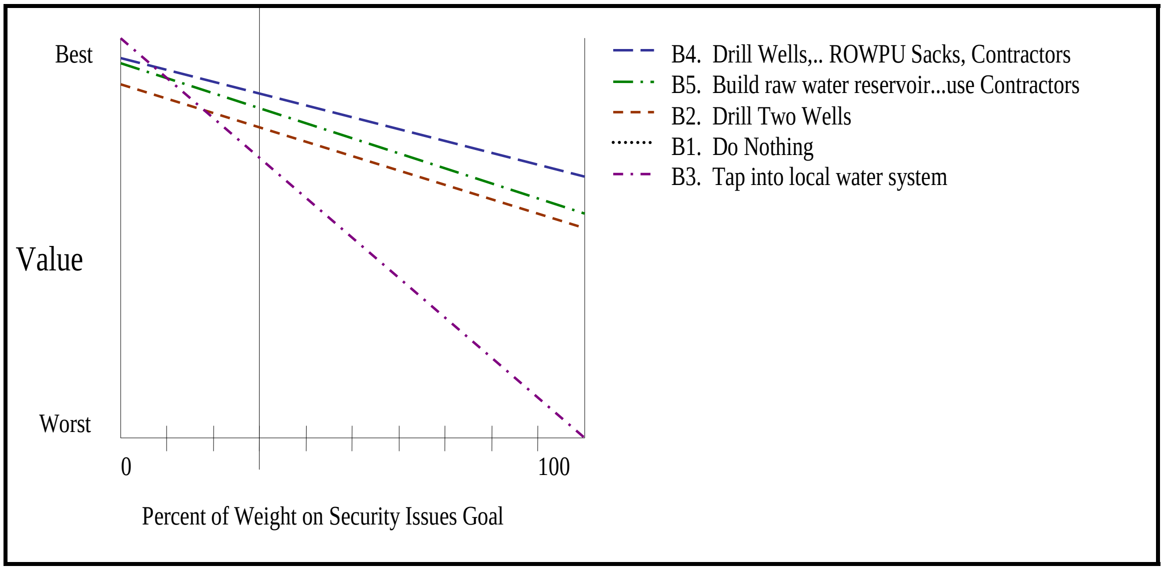

Figure 4-15. Sensitivity Analysis of Security for Bravostan

4.3 Charliestan Scenario

Charliestan is situated 5 miles from the nearest developed city, 1 mile from the nearest village, 20 miles from the nearest Army Camp, and 300 miles from a seaport. The base population is 700 with 200 Airmen and the rest Soldiers. The base mission is to provide medical evacuation and intelligence. The threat assessment includes attacks on convoys and insurgents from the city 5-miles away as well as the usual multi-national terrorist organizations. There has been non-specific chatter suggesting insurgents seek to target food and water supplies. Central Command (CENTCOM, 2002) recommends that bases stop using bottled water as soon as possible and either connect to the municipal water system, if force protection can be assured, or drill a minimum of two wells. The following sections cover the scoring and analysis of alternatives for Charliestan. The following sections cover the scoring and analysis of alternative for Charliestan. Relevant

project information is given in Table 4-5. Calculations supporting the cost measures are provided in Appendix C. Table 4-6 lists all of the measures used in the scoring.

Table 4-5. Project Information for Charliestan

Design Parameter	Value
Number of people served Design for	700 700
Stockpile Goal	4 weeks
Depth to serviceable water	500 feet
Operational life of infrastructure (Worst Case)	2 years
Distance to nearest municipal water supply	5 miles
Cost of Bottled Water Conservative price (real prices often higher)	10 cents per liter

Table 4-6. Measures for Charliestan's Initial Alternatives

Means Objective	Measure	Measure Unit	Upper Bound	Lower Bound	Alternatives				
					C1	C2	C3	C4	C5
Aesthetics									
	Color	Categorical	Excellent	Colored	Excellent	Slight	Slight	Slight	Slight
	Taste/Odor	Categorical	Excellent	Foul	Excellent	Slight	Excellent	Slight	Slight
	Temperature	Categorical	Cold	Hot	Cold	Warm	Warm	Hot	Hot
Package									
	Size	Categorical	1.5 Liter	5 Gal	1.5 L	Liter	Liter	Liter	Liter
	Type	Categorical	PET Bottle	Rubber Bladder	PET Bottle	Canteen	Canteen	Canteen	Canteen
Cost									
	Infrastructure	Cents/L	200	Zero	0.26	3.58	0.14	1.74	3.82
	O&M	Cents/L	200	Zero	10	0.36	0.01	1.76	1.97
	Waste Collection	Cents per Liter of water provided	10	Zero	1	0.01	0.01	0.01	0.01
Manpower									
	Airmen	People	6	Zero	1	2	1	2	2
	Contractors	People	10	Zero	0	0	0	0	0
Transport									
	Aircraft	Aircraft per week	5	Zero	0	0	0	0	0
	Trucks	Trucks/week	70	Zero	3.6	0.25	0	0.25	0.25
Reliability									
	Redundancy	Categorical	Triple	None	Double	Single	None	Single	Single
	Stockpile	Weeks	20	0	4	4	1	4	4
Safety									
	Accessibility	Categorical	Inside the Fence/Out of Sight/Watched Continuously	Outside the fence, not watched	Outside the fence, not watched	Inside the fence, visible	Outside the fence, not watched	Inside the fence, visible	Inside the fence, visible
	Detectability	Categorical	Very High	Low	Low	Very High	Low	Medium	Medium
Technical Water Quality									
	Water Quality	Categorical	Very High	Low	High	Very High	High	Very High	Very High

4.3.1 Step Seven — Alternative Scoring for Charliestan

Five alternatives were initially considered. The model calculates total value scores using the additive value function described in section 3.4. The results are shown in Figure 4-16, which presents the scores for the five alternatives considered initially, before sensitivity analyses suggested new alternatives. Notice the fourth and fifth alternatives, which were designed to score well considering the weights given by our decision-maker, scored well. The top-scoring alternative is one prescribed by CENTCOM (2002).

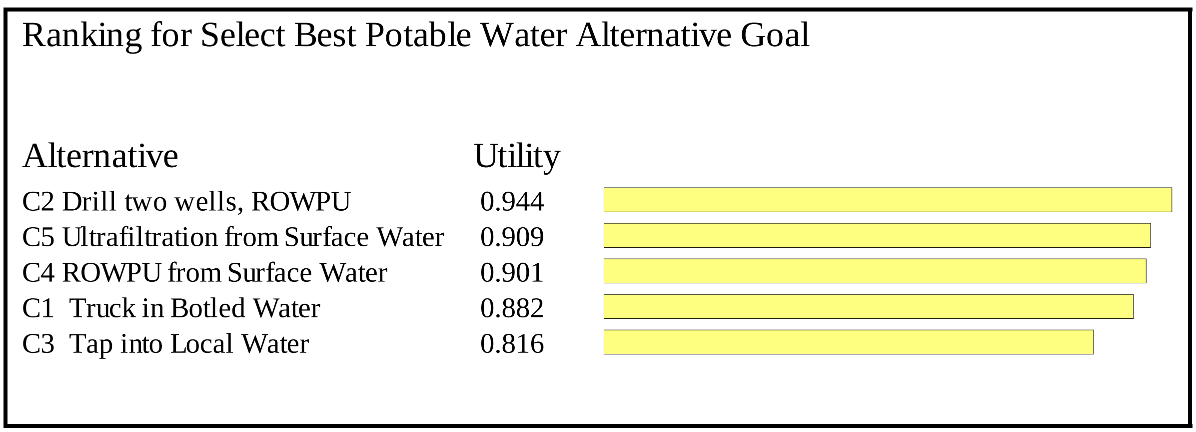

Figure 4-16. Initial Alternative Scoring for Charliestan

4.3.2 Step Eight – Deterministic Analysis for Charliestan

A deterministic analysis provides the decision maker with better insight as to why certain alternatives scored well and others scored poorly. For example Figure 4-17 displays how well each alternative performed for each fundamental objective. The biggest difference between the top three and the bottom two alternatives, again, is the

differences in value attributed to the *Security* objective. C1, the status-quo alternative, stands out for its lower score for the resources objective. This is because it requires so many trucks to support it.

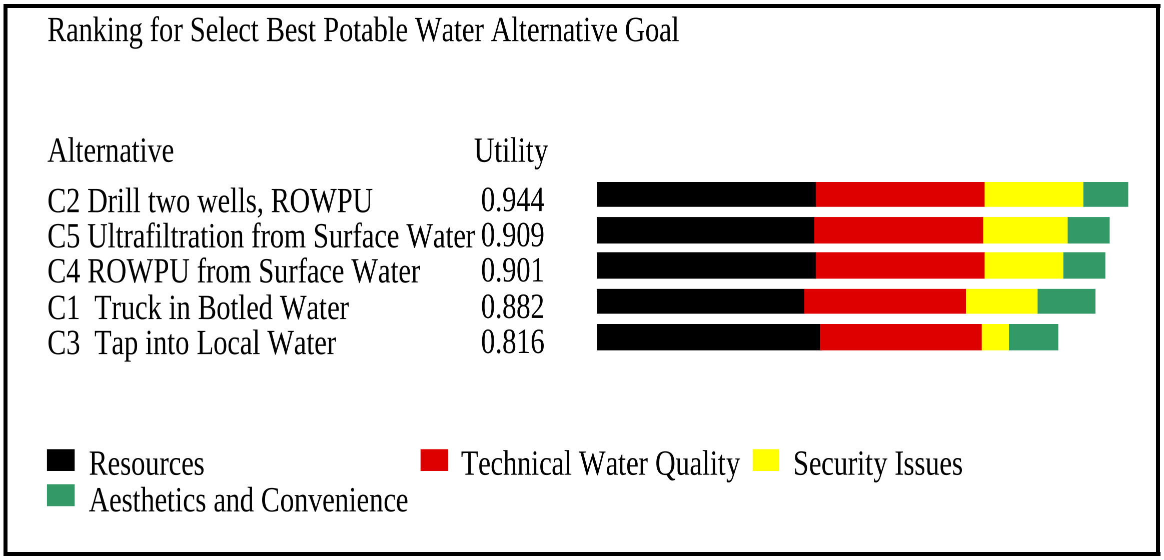

Figure 4-17. Fundamental Objective's Contributions for Charliestan

4.3.3 Step Nine – Sensitivity Analysis for Charliestan

First, a sensitivity of the fundamental objectives was conducted to see if any of these objectives was sensitive to changes in weighting. A measure is sensitive to changes in weighting if the rank ordering of the alternatives changes within a realistic probability of the weights (Jeoun, 2005). The sensitivity/insensitivity will be discussed after each analysis is performed in the following sections.

4.3.3.1 *Aesthetics and Convenience* Sensitivity Analysis for Charliestan

The sensitivity analysis shown in Figure 4-18 shows a worst place to first place reversal as the weight given *Aesthetics and Convenience* crosses over 34 percent. Here, in contrast to Alphastan and Bravostan, it seems the rank order may reverse if the decision maker's assessment of the weight given *Aesthetics and Convenience* is uncertain. Therefore, this ranking is sensitive to the *Aesthetics and Convenience* objective weighting.

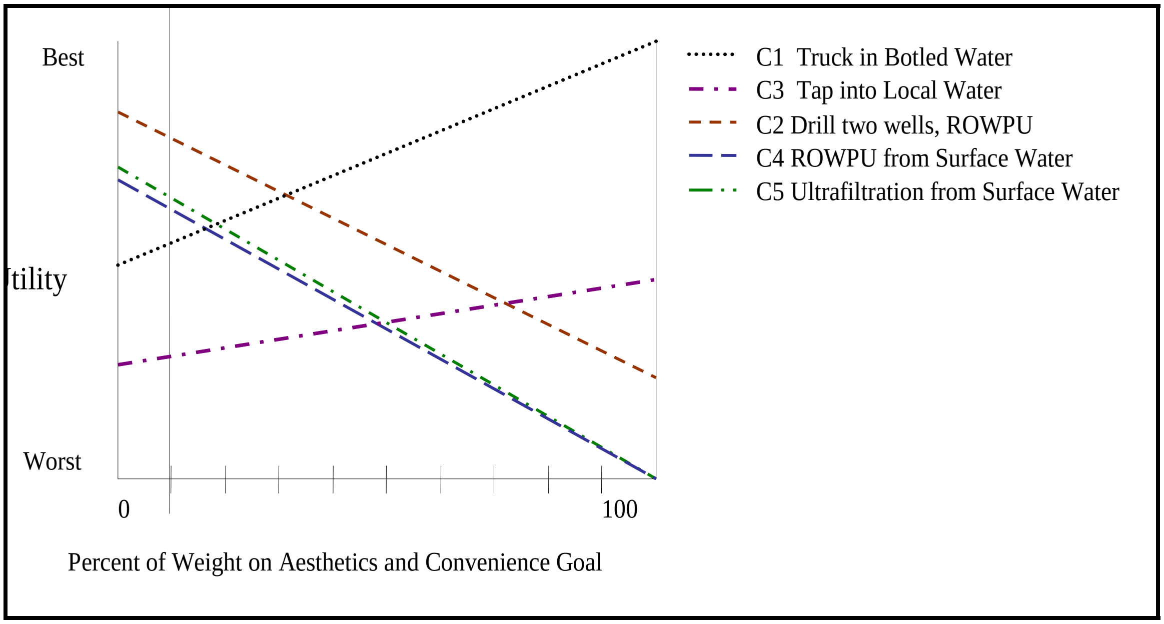

Figure 4-18. Sensitivity Analysis of *Aesthetics and Convenience* for Charliestan

Recall that Charliestan is near civilian populations and the Airmen may have ready access to water that is more aesthetically pleasing and may, therefore, become less satisfied with the taste of ROWPU water provided on base. While the model does not take this into account, a discussion amongst the squadron commanders may consider this situation and recommend to Colonel Cinnamon that the weight assigned to *Aesthetics*

should be greater. A glance at Figure 4-18 permits everyone to see how a greater assigned weight for *Aesthetics* may affect the decision. Further analysis is warranted.

Digging deeper into the causes of this sensitivity consider a sensitivity analysis on one of the underlying measures: *Aesthetics* (Figure 4-19). This graph appears the same as Figure 4-18 except the C3 line is rising here where it was flat before. Do not consider this small rise significant because the graphs do not represent changes in slope very well. Instead focus only changes to the rank order of the alternatives, which are the same for both figures. This suggests that the sensitivity to the fundamental objective is caused by the underlying *Aesthetics* sensitivity.

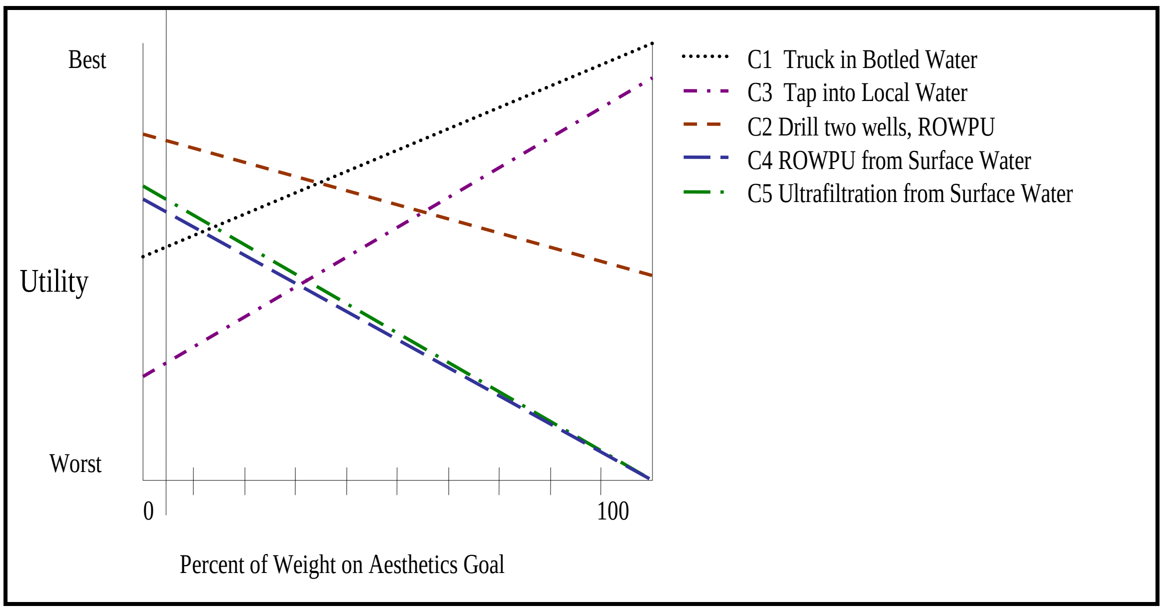

Figure 4-19. Sensitivity Analysis of *Aesthetics* for Charliestan

4.3.3.2 Resources Sensitivity Analysis for Charliestan

The top-scoring alternative (Drill Two Wells, Treat with ROWPU) holds the top position unless the weight given *Resources* is above 80 percent (Figure 4-20). It is unlikely the decision maker's approximation for the weight could be off by so much. Strictly speaking, *Resources* is insensitive. However, forecasting it seems likely in the course of a military campaign that the weight given resources might increase, but such a large swing seems relatively unlikely. Furthermore, the biggest expense of resources for our top alternative is an initial expense and not a continuing expense, so change in the weighting overtime should have no impact on the rank order of alternatives and so *Resources* is considered insensitive. However, if it did the worst alternative becomes the best alternative.

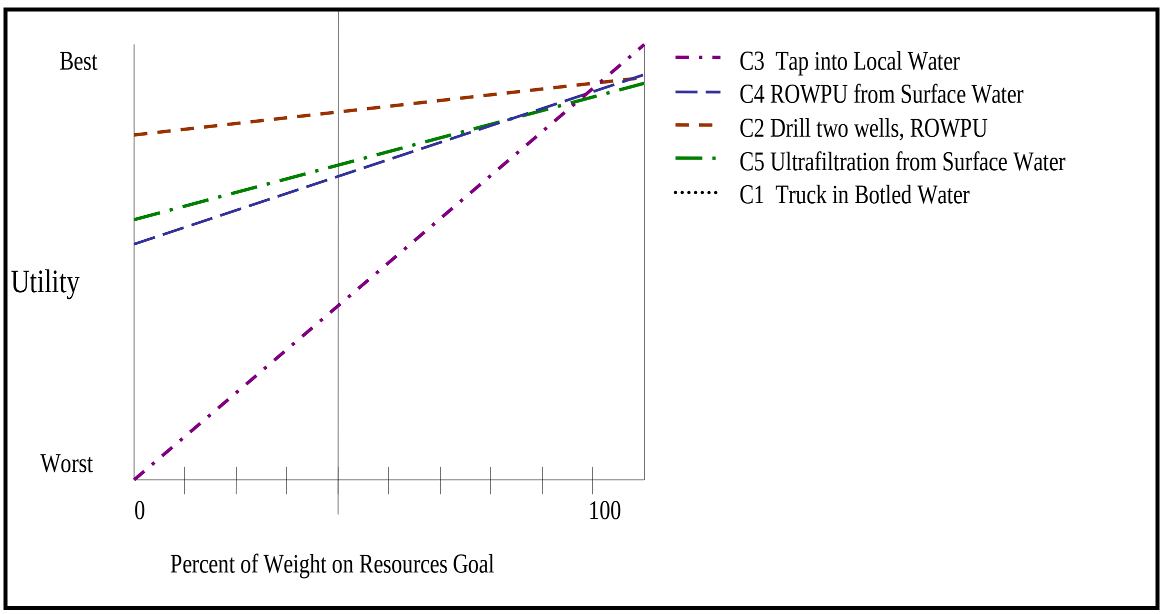

Figure 4-20. Sensitivity Analysis of *Resources* for Charliestan

The sensitivity of the rank order to *Aesthetics* and the proximity to locally available, unauthorized and potentially dangerous water alternatives for Airmen suggests consideration of a new alternative; one that has the benefits of our top-ranked alternative without the aesthetic tradeoffs. The Army has developed a way to bottle ROWPU water in the field. Suppose this, or similar technology was available for Charliestan. At the same time consider using contractors for manpower. Since field costs are not yet available for this technology some rough approximations are used to provide the speculative measures in Table 4-7. Alternatives C1 and C3 will be removed from further consideration because they fell short in meeting the security objective and to make the analysis of the remaining five objectives simpler. Alternatives C6 and C7 are new. The overall ranking of the new alternatives shows C6 with the highest score, Figure 4-21. The measures used for this evaluation are detailed in Table 4-8.

Table 4-7. All Alternatives Evaluated for Charliestan

#	Description	Source
~~C1~~	~~Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)~~	Do nothing, or Status-Quo alternative
C2	Drill at least two wells. Filtration by ROWPU, store, and distribute water using the normal ROWPU onion sacks.	Prescribed Alternatives
~~C3~~	~~Tap into local water system. No special filtration.~~	
C4	Same as (2) but minimize installation costs by using surface water instead of wells	Alternatives suggested by Weights
C5	Same as (4) but reduce operations and maintenance costs by using Ultrafiltration instead of ROWPU	
C6	Same as C2, but bottle the water directly from the ROWPU in PET bottles instead of storing product water in rubber bladders	Suggested by sensitivity analysis of *Aesthetics*
C7	Same as C6, but use contractors for the manpower	

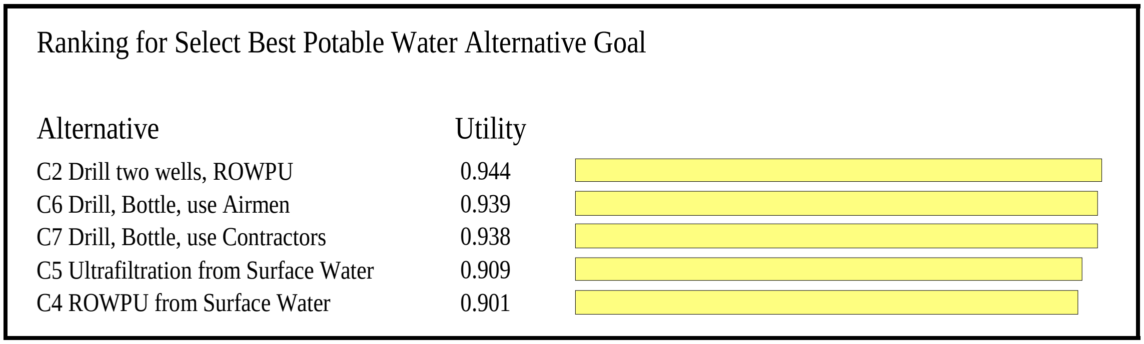

Figure 4-21. Alternative Scoring for Charliestan

Table 4-8. Measures for the Final Charliestan Alternatives

Means Objective	Measure	Measure Unit	Upper Bound	Lower Bound	Alternatives				
					C2	C4	C5	C6	C7
Aesthetics									
	Color	Categorical	Excellent	Colored	Slight	Slight	Slight	Excellent	Excellent
	Taste/Odor	Categorical	Excellent	Foul	Slight	Slight	Slight	Excellent	Excellent
	Temperature	Categorical	Cold	Hot	Warm	Hot	Hot	Cold	Cold
Package									
	Size	Categorical	1.5 Liter	5 Gal	Liter	Liter	Liter	1.5 Liter	1.5 Liter
	Type	Categorical	PET Bottle	Rubber Bladder	Canteen	Canteen	Canteen	PET Bottle	PET Bottle
Cost									
	Infrastructure	Cents per Liter	200	Zero	3.58	1.74	3.82	0.2	0.2
	O&M	Cents per Liter	200	Zero	0.36	1.76	1.92	6.0	27
	Waste Collection	Cents per Liter of water provided	10	Zero	0.1	0.05	0.1	1.0	1.0
Manpower									
	Airmen	People	6	Zero	2	1	2	4	0
	Contractors	People	10	Zero	0	0	0	0	4
Transport									
	Aircraft	Aircraft per week	5	Zero	0	0	0	0	0
	Trucks	Trucks per week	70	Zero	0.25	0.25	0.25	0.25	0.25
Reliability									
	Redundancy	Categorical	Triple	None	Single	None	Single	Single	Single
	Stockpile	Weeks	20	0	4	1	4	4	4
Safety									
	Accessibility	Categorical	Inside the Fence/Out of Sight/Watched Continuously	Outside the fence, not watched	Inside the fence, visible	Outside the fence, not watched	Inside the fence, visible	Inside the fence, visible	Inside the fence, visible
	Detectability	Categorical	Very High	Low	Very High	Low	Medium	Very High	Very High
Technical Water Quality									
	Water Quality	Categorical	Very High	Low	Very High	Very High	Very High	Very High	Very High

Recall that the reason new alternatives were considered was because the initial rankings for Charliestan were sensitive to changes in the weight given *Aesthetics*. A major benefit of value focused thinking versus alternative focused thinking is exploited here by considering the objective which made the rank order change. Focusing on the objective *Aesthetics* forces the analysis to look at alternatives (C6 and C7) that might not have otherwise been considered. Figure 4-22 shows how the new alternatives respond to change in the *Aesthetics* weight.

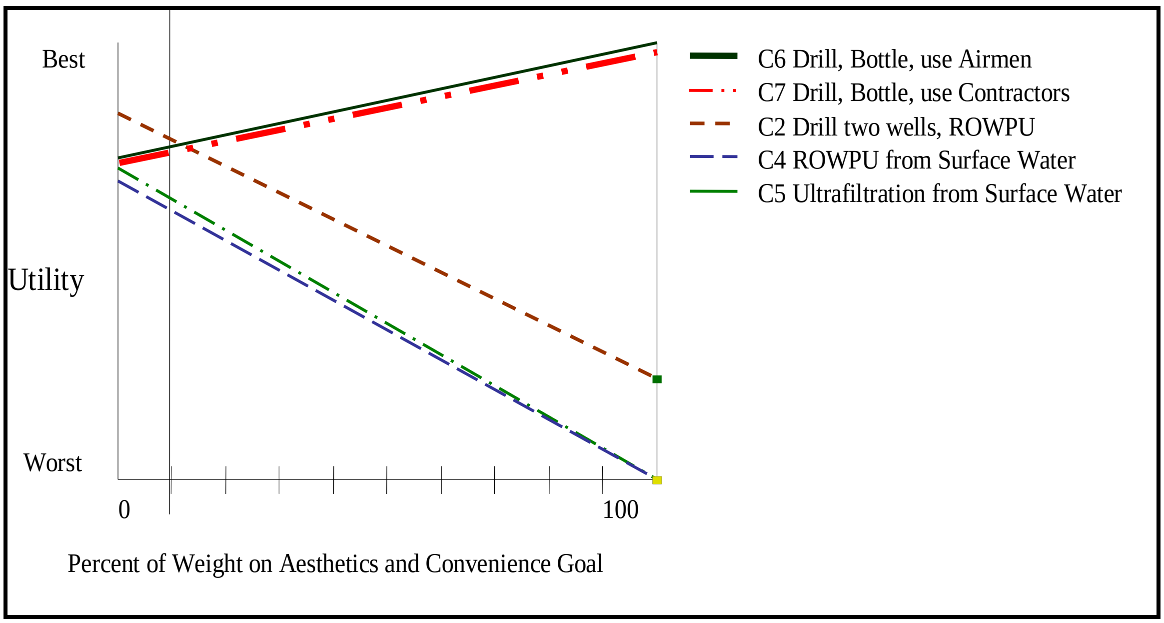

Figure 4-22. New Sensitivity Analysis of *Aesthetics and Convenience* for Charliestan

The new alternatives (C6 and C7) score better when the weight for *Aesthetics and Convenience* is greater than 10 percent and the old number one alternative scores better when it is below percent. Since the changeover point is very close to the weight our decision-maker gave the ranking of alternatives is sensitive to changes in this weight.

4.3.3.3 Security Sensitivity Analysis for Charliestan

Continuing with these new alternatives, the weight for Security is varied and the weights for the other objectives are adjusted proportionally to produce the final sensitivity analysis. This time the top-scoring alternative holds the top position unless the weight given *Security* is below approximately 5 percent (Figure 4-22). For any weight above 5 percent the slightly greater risk of using surface water as a source makes the two surface water based alternatives (C4 and C5) less attractive.

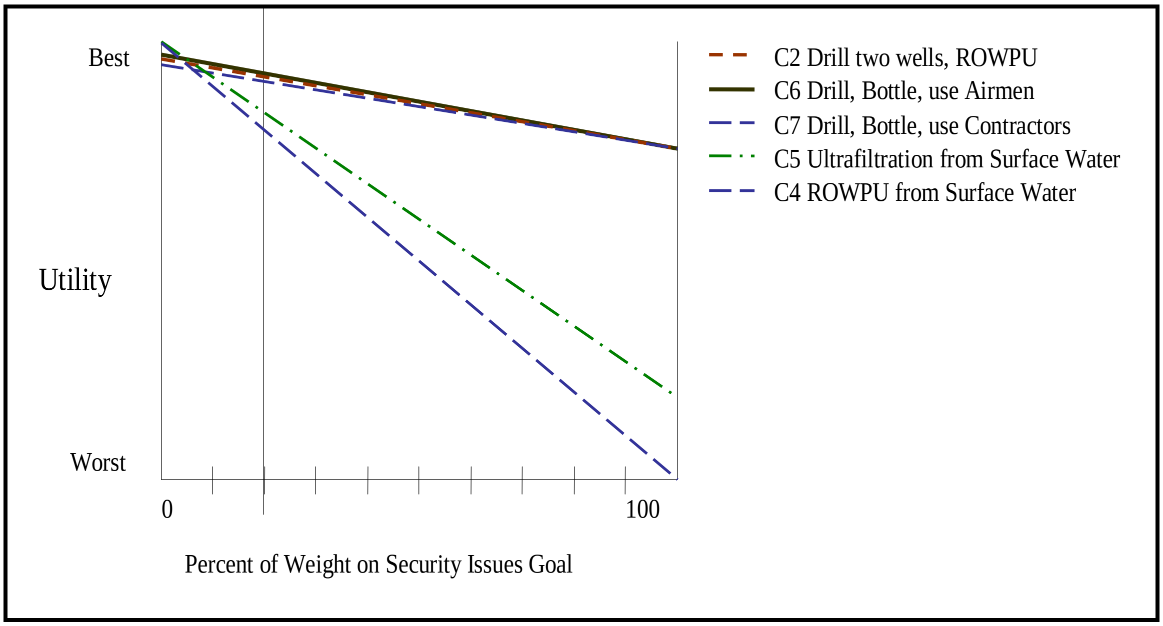

Figure 4-23. Sensitivity Analysis of *Security* for Charliestan

Given the scenario, which involves hostile enemies dependent on asymmetrical attacks, it seems unlikely any decision-maker would reduce the security objective to below 5 percent. Considering all the sensitivity analyses presented a decision-maker can be sure any of the top three choices are good choices.

Chapter 5. Summary and Conclusions

5.1 Overview

This chapter summarizes the results of this research effort, which applied the Value-Focused Thinking (VFT) methodology to the decision making process when selecting how to best provide water in Air Force field operations. Specifically, it addresses each of the four research questions defined in Chapter 1. It then outlines the strengths and limitations of the VFT decision model and recommends areas for further research on the subject. The last section of the chapter presents Step 10 of the VFT process: Conclusions.

5.2 Research Summary

Choosing the best means of providing water requires the examination and balancing of the often competing requirements, such as logistical effort, reliability, safety, and aesthetics. The importance or weighting of these requirements varies based on many objective situational factors as well as the more subjective values of the decision-maker. Therefore, this thesis applies the VFT model to this challenging decision. The VFT's ability to weigh the competing requirements of water supply provides the decision-maker with quantifiable measures to sort out the various options. This thesis effort applies the VFT model in a new way and may be the first time it has been applied toward decision making in the area of operational health.

5.3 Research Questions

Four research questions formed the basis of this research effort. Listed below is each question with its respective answer.

1. What are the characteristics, advantages, and disadvantages of different methods of providing potable water in a deployed location?

An important characteristic of each water provision method is the degree of access a potential saboteur may have to the water. Bottled water produced from foreign sources provides a high degree of accessibility in the manufacturing process as well as during transport. Water collected from a low-volume surface source, such as a ditch, can be easily contaminated. Water collected from a larger surface source such as a reservoir or lake is safer since the large volume would tend to dilute the contaminant. Water obtained from controlled wells present the least accessibility.

Another major characteristic that must be examined is the cost of water provision. This includes the initial cost as well as the continuing operational and maintenance costs. The bottled water method has minimal initial costs; the only requirement is storage space. However, the continuing operational costs vary considerably and can be huge. Water filtered from a well can have substantial initial costs, varying from $2,500 to upwards of $50,000 per well. Once the well is completed though, the operational costs are minimal (in the range of cents per thousand gallons). Water piped in from existing local municipalities provides even lower operational costs, but the initial costs can be great depending on how far the water must be piped.

Aesthetic properties of the water are also important. Bottled water from commercial sources is the most appealing to Airmen. Water filtered by ROWPU units, then highly chlorinated and stored in canvas or rubber bladders, may actually be safer; however, it is less pleasing to drink.

2. What is important to Air Force decision-makers when selecting a potable water supply method?

Decision-makers care about water quality, cost, security, reliability, and aesthetics. The importance of each these factors will vary based on the actual deployment situation as well as the decision-maker's values. Of course, the water provision method is also limited to the given resource constraints, which are primarily people and money.

3. Which types of potable water supply methods appear to be more suitable for different deployed regions?

The best water supply method has more to do with technical, tactical, and political aspects of the region rather than climate. These factors must be carefully considered and balanced to provide the appropriate water supply solution. Technical factors include the depth/availability of ground water of acceptable quality. Another technical factor is the number of eventual water consumers and the length of consumption; this affects how much upfront resource investment can be justified. Temperature is a technical factor as well as water consumption may vary as much as 400% depending on the climate.

Tactical factors include the strategies of military forces as well as the expected strategies of the enemy. Do the decision-makers put a high-value on morale,

convenience, and aesthetics or focus entirely on physical security? Will the enemy rely on asymmetrical attack? Similarly, political factors also influence the decision process. If financial support may diminish over time, initiatives that reduce the long-term operational cost should be considered. An operational goal to build or rebuild a nation's infrastructure would influence the selection of a more permanent water supply solution. Examples of how these considerations are incorporated into the decision-making process were presented with three different scenarios in Chapter 4.

4. How do changes in decision makers' values influence the outcome of the decision model?

In the three scenarios defined for this study, the requirements were given different weights by the decision-makers considering the notional scenarios provided. It was shown, particularly in the sensitivity analysis, that changes to the values (weights) may result in changes to the rankings of the alternatives produced by the model. The sensitivity analyses performed in Chapter 4 demonstrate that if the decision-maker modifies weights, the result can be a completely different ranking of the water provision alternatives. For an example, see the results of the sensitivity analysis involving *Aesthetics and Convenience* (See Figures 4-3, 4-12, 4-17).

5.4 Model Strengths

The research conducted for this thesis demonstrates several strengths associated with the decision model. The methodology is intuitively easy to use and understand; it defines requirements and breaks them down into fundamental parameters. It also

provides the flexibility of showing the objective nature of the decision as well as the subjective values of the decision-maker. It visually and clearly shows the tradeoffs involved by changing the weights of the different requirements. VFT also has the capability to model uncertainties and, as demonstrated in this research, it can lead to the development of additional, perhaps better, alternatives. However, perhaps its biggest strength is that the model focuses on pertinent and important parameters of the process, thereby avoiding unproductive discussions concerning less relevant factors.

5.5 Model Limitations

The application of the VFT model for this research began with a number of assumptions that limit the practicality of the results obtained. For example, the model assumes that available Airmen have the skills necessary to implement all the examined alternatives. Before the model could be used for more complex scenarios, it would have to be expanded to show the various Airmen categories and their skills. This would be a simple modification to make.

The model assumes the base would operate for a minimum of one year. Of course, upfront spending on a water provision alternative diminishes in significance the longer the expected life of the facility. In the case of temporary airbases established to operate for a few months, the model results may not be valid. However, the model could be adjusted to handle these short-term situations.

Cost estimates for the various alternatives were difficult to ascertain. This would prove difficult in real-world field activities as well. However, the model demonstrated that the cost requirement is not overly significant when choosing alternatives. For

example, even multiplying drilling costs by a factor of ten in the Alphastan scenario did result in any non-drilling alternatives outscoring the drilling alternatives.

5.6 Areas for Further Research

There are several areas of potential research that could improve the effectiveness of the VFT model developed in this research. For example, the model could be improved through more realistic discussions with actual Air Force decision makers and personnel at the Air Force Institute for Operational Health. Since drilling wells to provide water is usually the safest alternative, it would also be valuable to better understand advanced or extreme drilling methods. Applying oil recovery methods, such as deep drilling, directional drilling, and formation cracking, may prove useful to military operations.

Another area of research involves costs. The Air Force Civil Engineer Support Agency could enhance historical cost indices. This is particularly needed for alternatives not involving bottled water. Follow-on research could also develop cost models to predict these costs based on historical data. To estimate the costs of bottled water, this research depended on data provided by the General Accounting Office and anecdotal data. The GAO estimates varied depending on circumstances by several hundred percent. Therefore, the model could be improved if these estimates were verified and more narrowly constricted.

Finally, anecdotal evidence suggests that bottled water provided by some approved overseas suppliers occasionally test positive for fecal coliform. A study that examines the prevalence of unintentional contamination in bottled water would improve the model's estimate of the required safety requirement.

5.7 Step Ten: Final Conclusions

This researched clearly demonstrated that the use of value-focused thinking is an appropriate, effective, and powerful tool to evaluate alternative methods for the provision of water to Airmen in the field. Although results will certainly vary based on individual situations (e.g. temporary bases), the model shows that more of the decision-maker's values are met if water is supplied through the drilling of wells versus the continued reliance on commercial bottled water. More emphasis on drilling wells would not only potentially save hundreds of millions of dollars but would also provide a much safer water supply, thereby improving the chances for operational success. Finally, in consideration of the typical Airman's acceptance of drinking water, well water used in conjunction with the Army's field bottler may be just what the Air Force needs now.

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Safe Drinking Water Act Hotline 1-800-426-4791

National Well Water Association 1-614-761-1711

American Water Works Association (AWWA) 1-303-794-7711

Appendix B Summary of Measures

Index

1. Accessibility
2. Airlift
3. Airmen
4. Contractors
5. Color
6. Detectability
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8. O&M Costs
9. Redundancy
10. Size
11. Stockpile
12. Taste/Odor
13. Temperature
14. Trucks
15. Type
16. Waste Collection Costs
17. Water Quality

Measure: Accessibility

Definition: Degree of effort needed to disrupt or contaminate the water supply.

SDVF:

FOR EXAMPLE

Labels	Value
Inside the fence/out of sight/watched continuously	1.000
Inside the fence/visible/watched continuously	0.900
Outside the fence/visible/watched continuously	0.500
Outside the fence/visible/watched frequently	0.200
Outside the fence/visible/not watched	0.000

Category	Definition
Inside the fence	The entire water system is inside the base perimeter and the perimeter is secure.
Outside the fence	Some portion of the water system is outside the base perimeter or is in an area of the base lacking the security normally found inside the perimeter.
Out of sight	An enemy cannot identify the location of the water facilities from a vantage point outside the base perimeter.
Visible	An enemy can view the location of any key part of the water system from outside the base and may be able to target that facility with a rocket propelled grenade or other instrument. Portions of the water system that are outside the fence are considered visible.
Watched continuously	Facility is watched by assigned personnel 24 hours.
Watched frequently	Facility is watched deliberately, but not continuously. For example, it may be part of the security forces rounds.
Not watched	If it is not watched continuously or frequently as defined above, it is not watched as far as this model is concerned.

Comments: Although no alternative will be perfectly secure the boundaries of the value function allow a perfect score if The best we can do will get a perfect score.

Source: Estimated by subject matter experts.

Measure: Airlift

Definition: The number of Aircraft needed each week to support the alternative.

SDVF:

FOR EXAMPLE

Planes	Value
0	1.00
1	0.90
2	0.80
3	0.70
4	0.60
5	0.50
6	0.30
7	0.20
8	0.15
9	0.10
10	0.09

Comments: Although the scale is discrete we can still model it as continuous. The lower bound would be zero. The upper bound would be dependent on the location, and mission.

Source: Estimated by subject matter experts.

Measure: Airmen

Definition: The number of full-time equivalent Airmen needed to provide a particular alternative when it is running.

SDVF:

FOR EXAMPLE

Airmen	Value
0	1.00
1	0.90
2	0.80
3	0.70
4	0.50
5	0.25
6	0.10

Comments: Although the scale is discrete we can still model it as continuous. The lower bound would be zero Airmen. The upper bound would be dependent on the location and number of people served. For this example lets say the maximum number of airmen would be six. The total number would be a limited resource specified in the MANCAP.

Source: Estimated by subject matter experts.

Measure: Contractors

Definition: The number of full-time equivalent contractors needed to provide a particular alternative when it is running.

SDVF:

FOR EXAMPLE

Contractors	Value
0	1.00
1	0.95
2	0.80
3	0.75
4	0.70
5	0.65
6	0.60
7	0.50
8	0.45
9	0.40
10	0.20

Comments: Although the scale is discrete we can still model it as continuous. The lower bound would be zero contractors. The upper bound would be dependent on the location and number of people served. There may not be a hard limit on the number of contractors, but the number would be near the same as Airmen.

Source: Estimated by subject matter experts.

Measure: Color

Definition: The quality of water judged by viewing the water.

SDVF:

FOR EXAMPLE

Labels	Value
Excellent	1.000
Slight	0.750
Colored	0.100

Category	Definition
Excellent	No color or tint is visible.
Slight	Color is slight and only apparent when compared to colorless liquid.
Colored	Color is apparent.

Comments: Color can be measured quantitatively using a spectrophotometer; however this instrument is not always available in theater. The category definitions above are proposed as a field expedient.

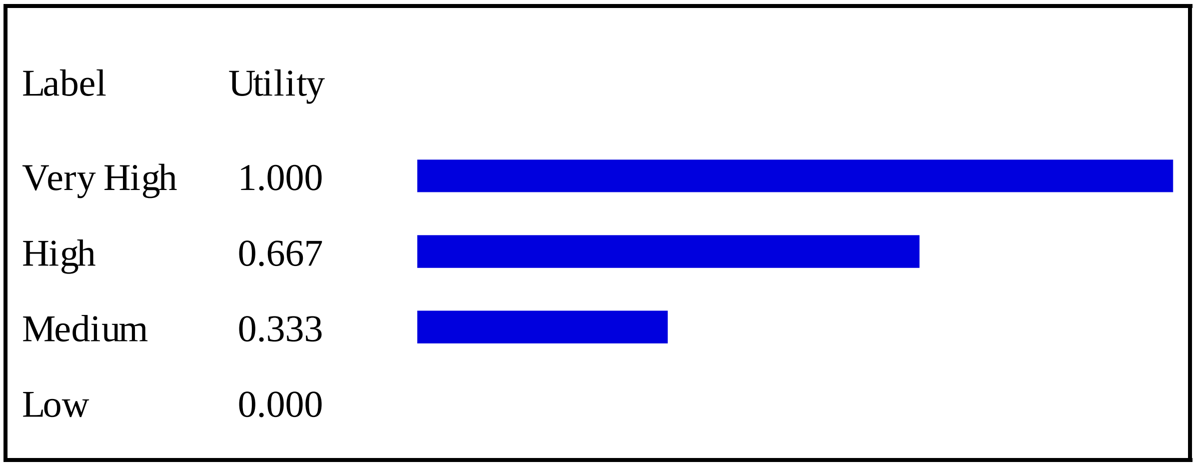
Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Detectability

Definition: Ability to detect tampering that is part of the alternative.

SDVF:

FOR EXAMPLE



Labels	Value
Very High	1.000
High	0.800
Medium	0.500
Low	0.100

Category	Definition
Very High	Probability an intrusion or containment will be detected is 100%.
High	Probability an intrusion or contaminant will be detected is 90% - 99%
Medium	Probability an intrusion or containment will be detected is 80-89%
Low	Probability an intrusion or containment will be detected is less than 80%

Comments: No alternative will be perfectly secure. The best we can do will get a perfect score.

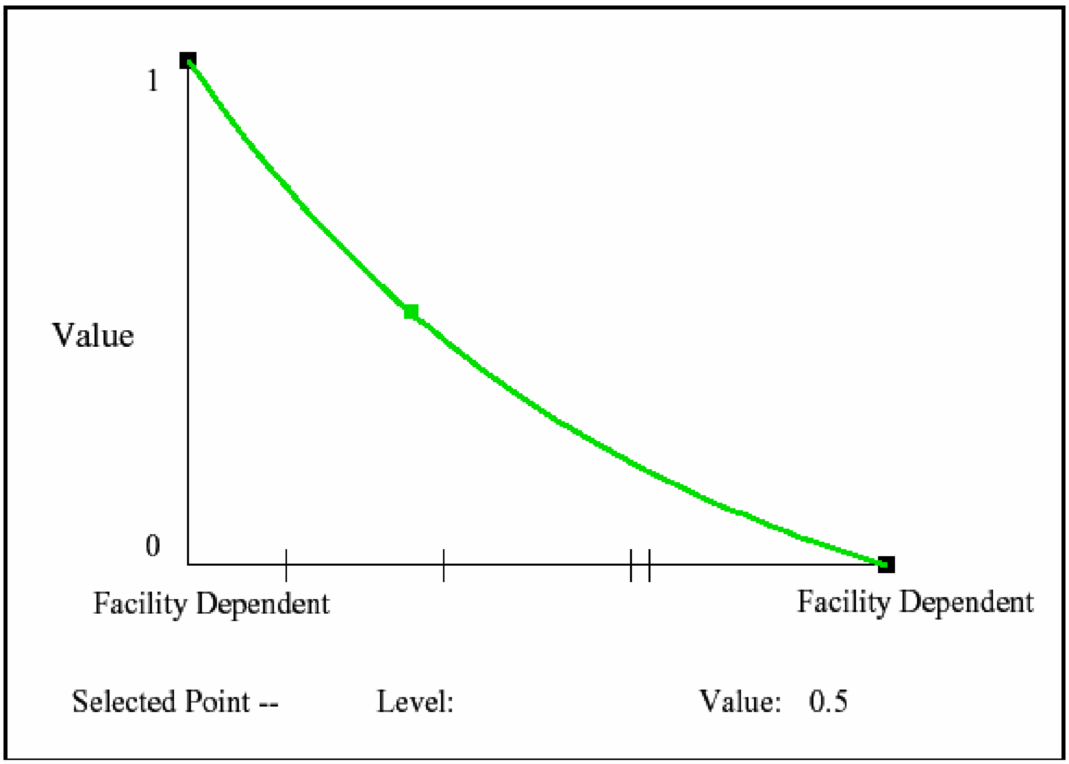
Source: Estimated by subject matter experts.

Measure: Infrastructure Costs

Definition: The cost, in cents per liter for constructing the necessary infrastructure, if any, for a particular alternative.

SDVF:

FOR EXAMPLE



Comments: The lower bound would be zero cost. The upper bound would be dependent on the location and number of people served. Examples of infrastructure may include wells, pipelines, tanks, reservoirs and shelters.

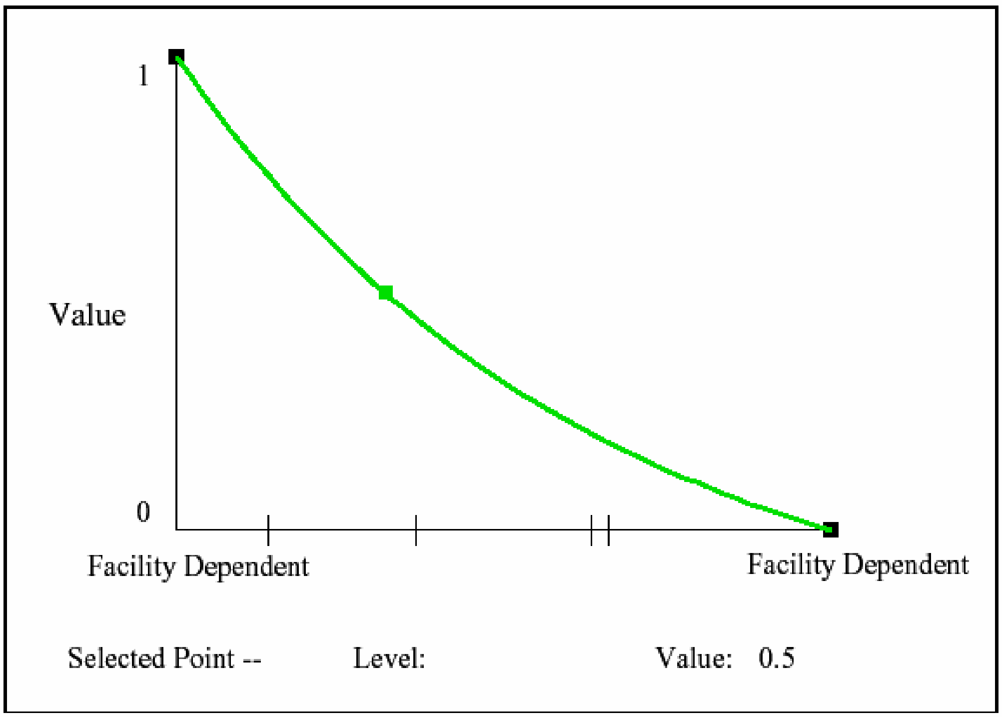
Source: Estimated by review of Air Force construction history data in ACES.

Measure: O&M Costs

Definition: The cost, in cents per liter for Operations and Maintenance.

SDVF:

FOR EXAMPLE



Comments: For a water treatment system it may include the cost of replacement parts, fuel and consumables. It does not include the cost of labor. The lower bound would be zero cost. The upper bound would be dependent on the location and number of people served.

Source: Estimated by supplier specifications

Measure: Redundancy

Definition: Number of backup systems

SDVF:

FOR EXAMPLE

Labels	Value
None	0.000
Single	0.750
Double	1.000

Comments: More redundancy is better, but returns diminish quickly for example, two levels of backup is only marginally better than one. Three levels is would normally be difficult to justify, unless we are talking about bottled water suppliers where it would be not so difficult to find four suppliers.

Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Size

Definition: Container size for individual use

SDVF:

FOR EXAMPLE

Labels	Value
1.5 Liter	1.000
Liter	0.900
0.5 Liter	0.750
Gallon	0.300
5-Gallon	0.250

Comments: Size is a convenience factor. Too large or too small makes the less convenient for things such as putting in a cooler or carrying.

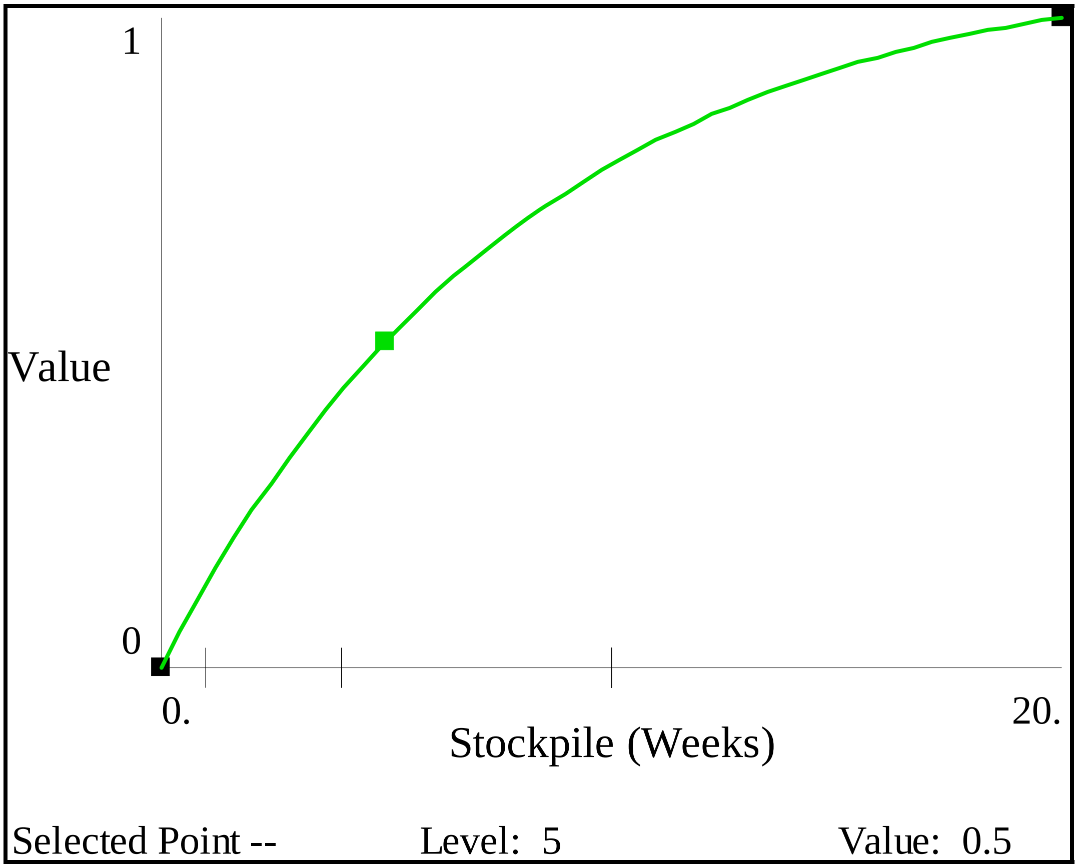
Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Stockpile

Definition: Number of weeks of potable water supply in storage

SDVF:

FOR EXAMPLE



Comments: More stockpile is better with diminishing returns at the high end of the scale. The high end is dependent on the location and scenario and the prospects for emergency resupply.

Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Taste/Odor

Definition: The quality of water judged by flavor and smell.

SDVF:

FOR EXAMPLE

Labels	Value
Excellent	1.000
Good	0.900
Slight	0.500
Foul	0.000

Category	Definition
Excellent	Taste is “good” to 95% of the Airmen asked.
Good	Taste is “good” to 90% of the Airmen asked.
Slight	Taste is “good” to 50% of the Airmen asked.
Foul	Taste is “good” to less than 50% of the Airmen asked.

Comments: Taste/odor is subjective. What tastes great to one person may taste/smell bad to another. If the alternative ranking is sensitive to this issue, it may be advisable to conduct a survey to more rigorously determine the values for each category.

Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Temperature

Definition: Direct measure of thermal energy using a thermometer.

SDVF:

FOR EXAMPLE

Labels	Value
Cold	1.000
Warm	0.700
Hot	0.100

Category	Definition
Cold	Below 55 degrees Fahrenheit.
Warm	Between 56 and 80 degrees Fahrenheit
Hot	Above 80 degrees Fahrenheit

Comments: Although temperature can be measured and valued on a continuous axis, the importance to aesthetics can be simplified by categorization.

Source: Estimated in the planning stages by Subject Matter Experts.

Measure: Trucks

Definition: The number of trucks needed each day to support the alternative.

SDVF:

FOR EXAMPLE

Trucks	Value
0	1.00
1-5	0.75
5-10	0.50
10-15	0.40
15-20	0.30
20-25	0.20
25-30	0.10

Comments: The SDVF takes on a stair-step appearance to model the concept of requiring an additional manning at the search area. In this formulation, which is notional, a single security inspector can check five trucks per day. The precise function will be location/scenario dependent.

Source: Estimated by subject matter experts.

Measure: Type

Definition: The type of container used to store the water..

SDVF:

FOR EXAMPLE

Type	Value
PET Bottle	1.00
Canteen	0.75
Metal Tank	0.50
Bladder	0.40

Comments: Each container type is associated various degrees of “appeal.” Individuals will have different preferences. The general sense of preferences is assumed to be that shown in the example above. If the model is sensitive to this measure it may be advisable to more rigorously determine the values of each container type.

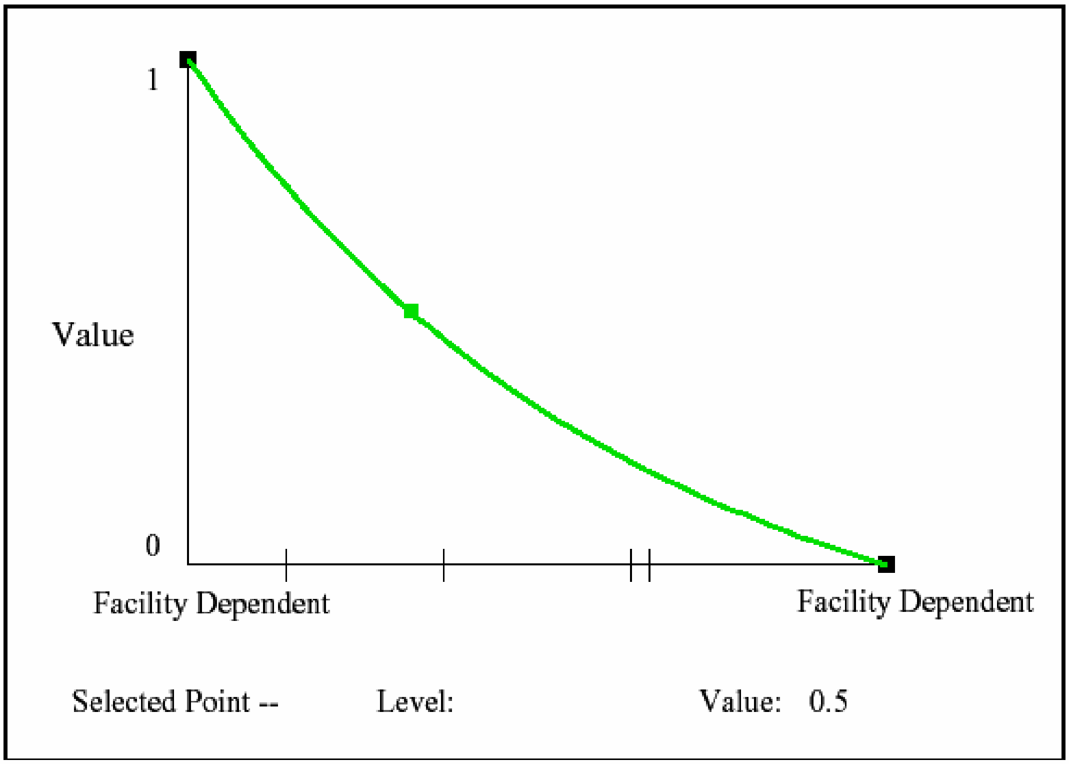
Source: Estimated by subject matter experts.

Measure: Waste Collection Costs

Definition: The cost, in cents per liter for collection of wastes associated with the alternative.

SDVF:

FOR EXAMPLE



Comments: The lower bound would be zero cost. The upper bound would be dependent on the location and number of people served.

Source: Estimated by SME.

Measure: Water Quality

Definition: Direct measure of thermal energy using a thermometer.

SDVF:

Labels	Value
Very High	1.000
High	0.950
Marginal	0.750
Low	0.100

Category	Definition
Very High	Meets the most stringent requirements established by the EPA, including the “long-term” deployment standards and the maximum contaminant level goals, which are goals but not required of water suppliers in the United States
High	Meets all of the requirements of the EPA and the “long-term” deployment standards, but not the EPA contaminant goals.
Marginal	Meets the short-term deployment standards
Low	Has contaminant above the short term deployment standards.

Comments: These categories simplify a long list of requirements by the EPA, FDA, and the Air Force. Normally our forces drink water that is of high quality as defined above. It is acceptable to Air Force doctrine to drink water of marginal quality for short durations.

Source: This is difficult to estimate in the planning stages.

Appendix C: Supporting Calculations

Index

Cost of Providing Fences and Shelters for Bottled Water

	Alphastan	Bravostan	Charliestan		
Narrative	**Quantity**	**Quantity**	**Quantity**	**Unit of Measure**	**Reference**
Drinkable water					
Daily drinking need	15	15	15	liters per person per day	AFMAN(I) 48-138, 2003
Base Population	2,000	3,000	700	people	
Design for	3,000	4,000	700	people	
Calculated	45,000	60,000	10,500	Liters per day	
Stockpile	**10**	**10**	**4**	**Weeks**	
	70	70	28	Days	
	3,150,000	4,200,000	294000	Liters	
	2,333	3,111	218	Pallets	1350 liters per pallet
	500	500	500	Pallets per shelter	
Unit Cost to build a fenced in shelter	$40,000	$40,000	$40,000	2007 Dollars	**Assumption**
Number needed for Stockpile	5	6	0		
Subtotal	$186,667	$248,889	$17,422	2007 Dollars	
Apply location factor	1.14	1.14	1.14	dimensionless	AFCESA, 2005 for Saudi Arabia
Total Installation Costs	$ 212,800	$ 283,733	$ 19,861	Adjust for Region	
Drinkable water quantity	45,000	60,000	10,500	Liters per day	
	16,425,000	21,900,000	3,832,500	Liters per year	
Time of use to spread cost	1	1	2	Years	
Liters to spread the cost	16,425,000	21,900,000	7,665,000	Liters	Only for hydration
Cost per unit of water	**1.30**	**1.30**	**0.26**	**Cents per liter**	

Compact Water Purification Units

	Charliestan		
Narrative	Quantity	Unit of Measure	Reference
	20	gallons per person per day	AFH 10-222, 1996:6
3.785 L per US Gal	75.7	Liters per person must be pumped	
Design for	700	people	
Calculated	52,990	liters per day must be filtered	
Subtotal	$ 85,185	each	producing 100,000 gallons per day
	$ 170,370	for two (redundancy)	http://www.hq.usace.army.mil/cepa/pubs/dec05/story18.htm
Apply location factor	1.14	dimensionless	USAF Regional Escalation Factors
Apply inflation	2%	annual	
Effective inflation factor	1.040	2 years from 2007 to 2005	
Total Installation Costs	$ 202,069	Adjusted for Region	AFCESA, 2005
	19,341,350	Liters per year pumped for hydration	
	38,682,700	Liters pumped in 2 years	
Cost per unit of water	**0.522**	**Cents per liter**	

Cost for Pipeline

	Alphastan	Bravostan	Charliestan		
Narrative	**Quantity**	**Quantity**	**Quantity**	**Unit of Measure**	**Reference**
Chose either 20 or 50	50	50	50	gallons per person per day	AFH 10-222, 1996:6
3.785 L per US Gal	189.25	189.25	189.25	Liters per person must be pumped	
Base Population	2,000	3,000	700		
Design for	3,000	4,000	2,000	people	
Calculated	567,750	757,000	378,500	Liters per day	
Share by two pumps	52	69	35	gallons per minute	
4 inch line sufficient					
Distance from Municipal System (Given)	25	10	5	miles	
Depth of wells, given by problem	132000	52800	26400	feet	
Rule of thumb factor	12	12	12	dollars per foot	AFCESA, 2002, page 3-22
Installation Costs	$1,584,000	$633,600	$316,800	Includes trenching, materials, and covering	
Drinkable water quantity	54,000	72,000	36,000	Liters per day	
Assume a one year life of project	19,710,000	26,280,000	13,140,000	Liters	
Subtotal	$ 1,584,000	$ 633,600	$ 316,800		
Apply location factor (Saudi Arabia)	1.14	1.14	1.14	dimensionless	AFCESA, 2005
Apply inflation	2%	2%	2%	annual	
Effective inflation	1.10	1.10	1.10	5 years from 2007 to 2002	
Total Installation Costs	$ 1,993,705	$ 797,482	$ 398,741	Adjust for Region	
Drinkable water quantity	45,000	60,000	30,000	Liters per day	
Assume a one year life of project	16,425,000	21,900,000	21,900,000	Liters	
	207,228,750	276,305,000	276,305,000	Liters per year pumped for hydration	
Cost per unit of water	**0.96**	**0.29**	**0.14**	**Cents per liter**	

Cost for Reservoir Construction

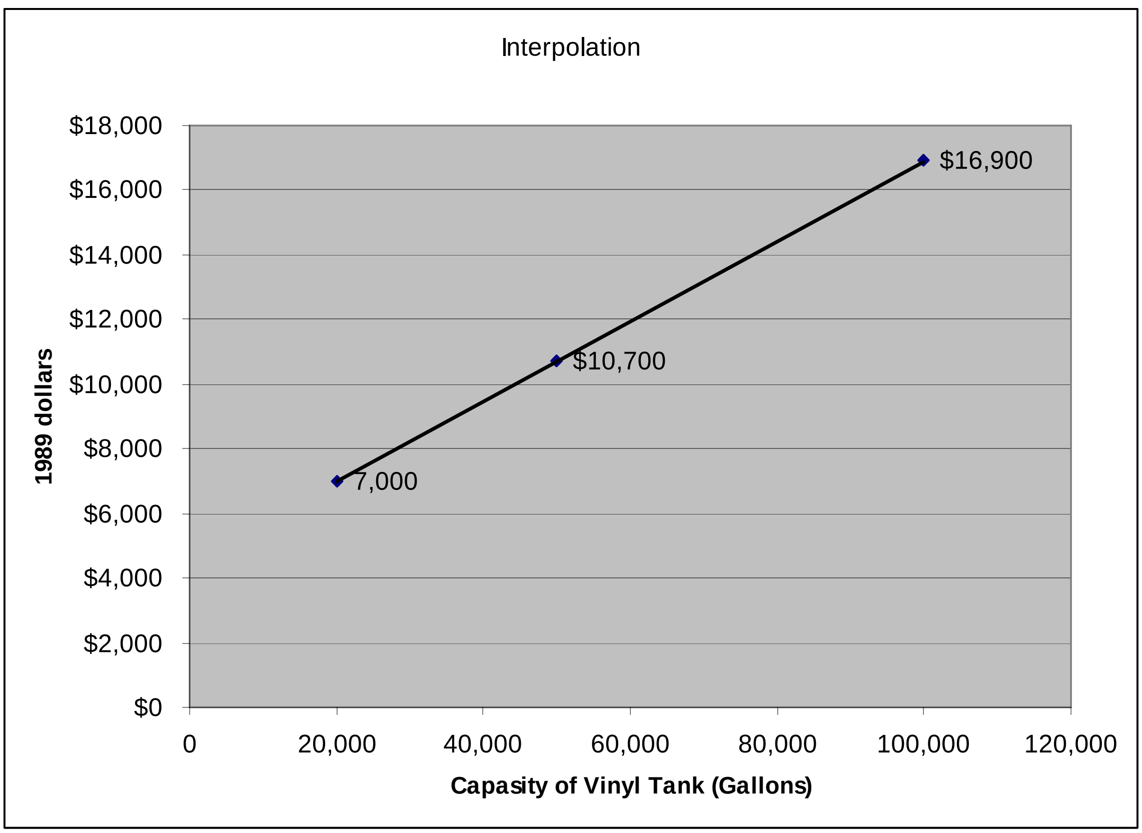
	Alphastan	Bravostan	Charliestan	Units of Measure	Reference
Depth	20	20	20	feet	
Length	267.5	267.5	267.5	feet	
Width	50	50	50	feet	
Volume	267,500	267,500	267,500	cubic feet	
	7.48	7.48	7.48	gallons per cubic foot	
	2,000,900	2,000,900	2,000,900	gallons	
	9,907	9,907	9,907	cubic yards	
	2	2	2	per cubic yard	Means 1998
	$19,814.81	$19,814.81	$19,814.81		
Inflation (9 years)	1.1951	1.1951	1.1951		
Apply location factor	1.14	1.14	1.14	dimensionless	
Total Installation Costs	$ 26,996	$ 26,996	$ 26,996	Adjust for Region	AFCESA, 2005
Drinkable water quantity	45,000	60,000	10,500	Liters per day	
	16,425,000	21,900,000	3,832,500	Liters per year	
Assume a one year life of project	16,425,000	21,900,000	7,665,000	Liters	
Cost per unit of water	**0.16**	**0.12**	**0.35**	**Cents per liter**	

Cost for Tanks

Installation Cost for Tanks	Alphastan	Bravostan	Charliestan		
Narrative	**Quantity**	**Quantity**	**Quantity**	**Unit of Measure**	**Reference**
Drinkable water	15	15	15	liters per person per day	AFMAN(I) 48-138, 2004
Base Population	2,000	3,000	700	people	
Design for	3,000	4,000	2000	people	
Calculated	45,000	60,000	30000	Liters per day	
Stockpile	10	**10**	10	Weeks	
	70	70	70	Days	
	3,150,000	4,200,000	2100000	Liters	
	832,232	1,109,643	554822	Gallons	
Means	Fiberglass	Bladder	Bladder		
Normal Capacity	50,000	20,000	20,000	Gallons	
Unit Cost	$40,000	$12,000	$12,000	2007 Dollars	Interpolated from Means
Number needed for Stockpile	16.6	**55.5**	27.7		Fiberglass costs estimated by AFCESA (email, 28 Feb 2006)
Subtotal	$665,786.00	$665,786.00	$332,893.00	2007 Dollars	
Apply location factor	1.14	1.14	1.14	dimensionless	Used Saudi Arabia because Alphastan is fictitious
Total Installation Costs	$ 758,996	$ 758,996	$ 379,498	Adjusted for Region	AFCESA, 2005
Drinkable water quantity	45,000	60,000	30,000	Liters per day	
Assume a one year life of project	16,425,000	21,900,000	10,950,000	Liters	
	16,425,000	21,900,000	10,950,000	Liters pumped for hydration	
Cost per unit of water	4.62	3.47	3.47	**Cents per liter**	

Estimating Cost of Vinyl Tanks

Mean's Interpolation		
gallon	1989 Dollars	
100,000	$16,900	
50000	$10,700	
20000	$ 7,000	by eyeball
Years	18	
Inflation	3%	
effective inflation	1.702433061	
2007 Dollars	$ 11,917	



Calculating the number of trucks

Narrative	Alphastan	Bravostan	Charliestan	Units of Measure
	15	15	15	liters per person
	2,000	3,000	700	people
	30,000	45,000	10,500	liters per day
	1.5	1.5	1.5	liters per bottle
	20,000	30,000	7,000	bottles per day
Purchase price	$ 0.50	$ 0.50	$ 0.50	dollars per liter
	18	18	18	bottles per case
	15	15	15	cases per level
	5	5	5	levels per pallet
	75	75	75	cases per pallet
	1350	1350	1350	bottles per pallet
	14.8	22.2	5.2	pallets per day
	12	12	12	pallets per truck
	1.2	1.9	0.4	trucks per day
	$ 105,000	$ 157,500	$ 36,750	Dollars per week
	8.6	**13.0**	**3.0**	**trucks per week**

Installation Costs for Wells

Narrative	Alphastan Quantity	Bravostan Quantity	Charliestan Quantity	Unit of Measure	Reference
Chose either 30 or 50	20	20	20	gallons per person per day	AFH 10-222, 1996
3.785 L per US Gal	75.7	75.7	75.7	Liters per person must be pumped	
Base Population	2,000	3,000	700		
Design for	3,000	4,000	700	people	
Share by two pumps	20.8	27.8	4.9	gallons per minute	
21 GPM is within range of pumps					http://www.aquascience.net
Depth of wells, given by problem	500	500	500	feet	
21 GPM pumps come in 4" size	4	4	4	inch	
Well drilling cost factor	$28.50	$28.50	$28.50	per linear foot	Means 1998
Cost for two wells	$ 28,500	$ 28,500	$ 28,500	for two wells, 1998 USA	
Pump purchase cost	$ 3,824	$ 3,824	$ 3,824	2 ea.	http://www.deanbennett.com
Subtotal	$ 32,324	$ 32,324	$ 32,324		
Apply location factor	1.14	1.14	1.14	dimensionless	USAF Regional Escalation Factors
Apply inflation	2%	2%	2%	annual	
Effective inflation factor	1.195	1.195	1.195	9 years from 2007 to 1998	
Total Installation Costs	$ 44,038	$ 44,038	$ 44,038	Adjusted for Region	AFCESA, 2005
	82,891,500	110,522,000	38,682,700	Liters per year	
Cost per unit of water	**0.053**	**0.040**	**0.114**	**Cents per liter**	

A1

#	Description			
A1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)			
		Qty	**Units**	**Comments**
	Installation Costs			Build fences and shelters for storing bottled water
	Unit Cost for Installation	**1.30**	cents per liter	See bottled water worksheet for details
	TOTAL	**1.30**	cents per liter	
	O&M			
		10	cents per liter	Purchase Costs
	Labor (If contractor)	0.00		Use airmen
	TOTAL	**10.00**	cents per liter	
	Waste			
	Bottle Collection	1	cents per liter	Assumed
	TOTAL	**1.00**	cents per liter	

A2

#	Description			
A2	Drill at least two wells. Filtration by ROWPU, store and distribute water using the normal ROWPU onion sacks.			
		Qty	**Units**	**Comments**
	Installation Costs			
	2 wells	0.05	cents per liter	50 bladders needed for 4 weeks stockpile
	50 bladders	3.04	cents per liter	20,000 gallons each
	TOTAL	**3.09**	cents per liter	
	O&M			
	Maintenance	0.31	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.31**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

A3

#	Description			
A3	Tap into local water system. No special filtration.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Pipeline	0.96	cents per liter	
	TOTAL	**0.96**	cents per liter	
	O&M			
	Maintenance	0.10	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.10**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

A4

#	Description			
A4	Same as (A2), but store water in multiple and separated fiberglass tanks out of direct sunlight to increase stockpile and reduce the dosage of chlorine necessary to maintain a residual.			
		Qty	Units	Comments
	Installation Costs			
	2 wells	0.05	cents per liter	
	20 fiberglass tanks	4.62	cents per liter	50,000 gallons each
	TOTAL	**4.62**	cents per liter	
	O&M			
	Maintenance	0.46	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.46**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

A5

#	Description			
A5	Build reservoir for raw surface water to reduce accessibility, filter by ROWPU, and store water in a sufficient number of ROWPU storage bladders to ensure 10 weeks of stockpile.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Reservoir	0.16	cents per liter	
	50 bladders (10 weeks)	3.04	cents per liter	50,000 gallons each
	TOTAL	**3.20**	cents per liter	
	O&M			
	labor	0.00	cents per liter	Use Airmen
	maintenance	0.32	cents per liter	Assumed to be 10% of installation
	ROWPU Filtration	6	cents per gallon	Assume high end of ROWPU cost for surface water
		1.59	cents per liter	
	TOTAL	**1.91**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

A6

#	Description			
A6	Drill at least two wells. Filtration by ROWPU, store water in fiberglass tanks, use contractors instead of airmen			
		Qty	**Units**	**Comments**
	Installation Costs			
	2 wells	0.05	cents per liter	50 bladders needed for 4 weeks stockpile
	50 bladders	3.04	cents per liter	20,000 gallons each
	TOTAL	**3.09**	cents per liter	
	O&M			
	contractors			Use Contractors
	Yearly wage	$200,000	per person per year	
	Number necessary	4		
	Total Wages	$800,000	per year	
	Number of Liters per year	16,425,000		
	Labor	4.87	cents per liter	
	Maintenance	0.31	cents per liter	Assumed to be 10% of installation
	TOTAL	**5.18**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

B1

#	Description			
B1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)			
		Qty	**Units**	**Comments**
	Installation Costs			Build fences and shelters for storing bottled water
	Unit Cost for Installation	**1.30**	cents per liter	See bottled water worksheet for details
	TOTAL	**1.30**	cents per liter	
	O&M			
		10	cents per liter	Purchase Costs
	Labor (If contractor)	0.00		Use airmen
	TOTAL	**10.00**	cents per liter	
	Waste			
	Bottle Collection	**1**	**cents per liter**	Assumed
	TOTAL	**1.00**	cents per liter	

B2

#	Description
B2	Drill at least two wells. Filtration by ROWPU, store and distribute water using the normal ROWPU onion sacks.

		Qty	Units	Comments
	Installation Costs			
	2 wells	0.04	cents per liter	50 bladders needed for 4 weeks stockpile
	22 bladders	3.47	cents per liter	20,000 gallons each
	TOTAL	**3.51**	cents per liter	
	O&M			
	Maintenance	0.35	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.35**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

B3

#	Description			
B3	Tap into local water system. No special filtration.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Pipeline	0.29	cents per liter	
	TOTAL	**0.29**	cents per liter	
	O&M			
	Maintenance	0.03	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.03**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

B4

#	Description			
B4	Same as (B2), but store water a sufficient number of ROWPU storage bladders to ensure 10 weeks of stockpile, provide labor by contactors.			
		Qty	**Units**	**Comments**
	Installation Costs			
	2 wells	0.040	cents per liter	
	67 bladders	3.466	cents per liter	50,000 gallons each
	TOTAL	**3.51**	cents per liter	
	O&M			
	contractors			Use Contractors
	Yearly wage	$200,000	per person per year	
	Number necessary	4		
	Total Wages	$800,000	per year	
	Number of Liters per year	21,900,000		
	Per liter cost of contractors	3.65	cents per liter	
	maintenance	0.35	cents per liter	Assume 10% of installation
	ROWPU filtration	3	3 cents per gallon	
		0.79	cents per liter	
	TOTAL	**4.80**	**cents per liter**	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

B5

#	Description			
B5	Build reservoir for raw surface water to reduce accessibility, filter by ROWPU, and store water in a sufficient number of ROWPU storage bladders to ensure 10 weeks of stockpile, and provide labor by contractors.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Reservoir	0.12	cents per liter	
	56 bladders (10 weeks)	3.47	cents per liter	50,000 gallons each
	TOTAL	**3.59**	cents per liter	
	O&M			Use Contractors
	contractors			
	Yearly wage	$200,000	per person per year	
	Number necessary	4		
	Total Wages	$800,000		
	Number of Liters per year	21,900,000		110,522,000
	Per liter cost of contractors	3.65	cents per liter	
	maintenance	0.36	cents per liter	Assumed to be 10% of installation
	ROWPU Filtration	6	cents per gallon	Assume high end of ROWPU cost for surface water
		1.59	cents per liter	
	TOTAL	**5.60**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

C1

#	Description			
C1	Bottled water supplied from regional suppliers, shipped overland by truck. Assume we have three suppliers (double-redundancy)			
		Qty	**Units**	**Comments**
	Installation Costs			Build fences and shelters for storing bottled water
	Unit Cost for Installation	0.26	cents per liter	See bottled water worksheet for details
	TOTAL	**0.26**	cents per liter	
	O&M			
		10	cents per liter	Purchase Costs
	Labor (If contractor)	0.00		Use airmen
	TOTAL	**10.00**	cents per liter	
	Waste			
	Bottle Collection	**1**	**cents per liter**	Assumed
	TOTAL	**1.00**	cents per liter	

C2

#	Description			
C2	Drill at least two wells. Filtration by ROWPU, store and distribute water using the normal ROWPU onion sacks.			
		Qty	**Units**	**Comments**
	Installation Costs			
	2 wells	0.11	cents per liter	50 bladders needed for 4 weeks stockpile
	12 bladders	3.47	cents per liter	20,000 gallons each
	TOTAL	**3.58**	cents per liter	
	O&M			
	Maintenance	0.36	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.36**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

C3

#	Description			
C3	Tap into local water system. No special filtration.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Pipeline	0.14	cents per liter	
	TOTAL	**0.14**	cents per liter	
	O&M			
	Maintenance	0.01	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**0.01**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

C4

#	Description			
C4	Filter surface water by ROWPU, store and distribute water using the normal ROWPU onion sacks.			
		Qty	**Units**	**Comments**
	Infrastructure			
	Reservoir	0.35	cents per liter	Reservoir
	12 bladders	1.39	cents per liter	20,000 gallons each
	TOTAL	**1.74**	cents per liter	
	O&M			
	ROWPU filtration	6	6 cents per gallon	Surface water has more solids
		1.59	cents per liter	
	Maintenance	0.17	cents per liter	Assumed to be 10% of installation
	Labor	0.00		Use airmen
	TOTAL	**1.76**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

C5

#	Description			
C5	Build reservoir for raw surface water to reduce accessibility, filter by ROWPU, and store water in a sufficient number of ROWPU storage bladders to ensure 10 weeks of stockpile.			
		Qty	**Units**	**Comments**
	Installation Costs			
	Reservoir	0.35	cents per liter	
	12 bladders (4 weeks)	3.47	cents per liter	50,000 gallons each
	TOTAL	**3.82**	cents per liter	
	O&M			
	labor	0.00	cents per liter	Use Airmen
	maintenance	0.38	cents per liter	Assumed to be 10% of installation
	ROWPU Filtration	6	cents per gallon	Assume high end of ROWPU cost for surface water
		1.59	cents per liter	
	TOTAL	**1.97**	cents per liter	
	Waste			
	Not much	0.01	cents per liter	100x less than bottles
	TOTAL	**0.01**	cents per liter	

C6

#	Description			
C6	Drill at least two wells. Filtration by ROWPU, bottle into PET bottles.			
		Qty	**Units**	**Comments**
	Installation Costs			
	2 wells	0.11	cents per liter	50 bladders needed for 4 weeks stockpile
	PET bottler	0.09	cents per liter	Assume less than wells including salvage value
	TOTAL	**0.20**	cents per liter	
	O&M			
	Maintenance	0.02	cents per liter	Assumed to be 10% of installation
	Materials	5.98	cents per liter	Assumed to be nearly that of purchased bottles
	Labor	0.00		Use airmen
	TOTAL	**6.00**	cents per liter	
	Waste			
	Not much	1	cents per liter	same as bottles
	TOTAL	**1.00**	cents per liter	

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14. ABSTRACT

Because of potential improvements to water security and cost savings, military decision makers may want to consider new means of providing potable water to Airmen in deployed locations. Drilling for water and field bottling show great potential because of the increased security and lower per unit cost when compared to bottled water from approved sources. However, the selection of the best means to supply water is a hard decision which must balance multiple objectives (e.g., security, palatability, and convenience) against limited resources (e.g., cost, airlift, trucks, and personnel).

A multi-objective decision analysis model quantifies a decision-maker's values regarding the many different means of providing potable water. Consisting of four fundamental values and seventeen measures, the model captures the Air Force's objectives. Using three different notional bases, the model was tested by evaluating five initial alternatives for each base. Sensitivity analysis was also conducted to provide additional insight into the tradeoffs and to generate potentially even better alternatives which were tailored to the specific location and decision-maker's objectives. More emphasis on drilling wells could save hundreds of millions of dollars and provide a much safer water supply, thereby improving the chances for operational success.

15. SUBJECT TERMS

Operational health, water security, potable water, Decision Analysis

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